VOLCANOES OF NORTH AMERICA

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VOLCANOES OF NORTH AMERICA

A READING LESSON FOR STUDENTS OF GEOGRAPHY AND GEOLOGY

BY

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INTRODUCTION

In the present volume the Western Hemisphere is considered as being divided into two portions; namely, North and South America. Central America is included in the northern division for the reason that the student of volcanic phenomena finds a break in the volcanic belts which follow the western borders of the two continents, at the Isthmus of Darien.

The series of active and recently extinct volcanoes forming the major part of the Windward islands, separating the Caribbean Sea from the Atlantic, will not be considered, as it is most intimately associated with the geography and geology of South America. Although Iceland is more closely connected geographically with America than with Europe, its political association with the Old World, and the fact that it has frequently been described by European travellers, make it convenient to omit it from the present discussion.

Among the leading physical features of the southern prolongation of the North American continent comprising Mexico and the Central American republics, are numerous still steaming and recently extinct volcanoes, some of which have had their birth since the Spanish conquest. This region also furnishes examples of violent volcanic eruptions, one of which is probably second, in

reference to intensity, among similar events witnessed by civilized man.

Many phases of volcanic phenomena occur in the western portion of the United States. The lofty volcanic mountains of northern California, Oregon, and Washington are among the most beautiful examples of their class to be found in the world. To the eastward of these giant peaks, whose fiery glow has been replaced by the sheen of snow-fields and glaciers, lies a vast lava-covered region, the only known parallel of which, in the extent and thickness of the once molten rocks, occurs in northwestern India.

In Alaska volcanic energy is still active, and more than a score of volcanoes have been in eruption since the voyages of Bering in 1725–30.

It is the character and history of this vast volcanic belt, reaching from the tropical shores of Costa Rica to the western extremity of the bleak and inhospitable Aleutian islands, that the attention of students of geology and geography is here invited.

The object of this book is to make clear the principal features of volcanoes in general, and to place in the hands of students a concise account of the leading facts thus far discovered, concerning the physical features of North America which can be traced directly to the influence of volcanic action.

It is hoped that the accounts of volcanic eruptions here brought together and the discussions of the accompanying topographic changes, will lead the reader to consult some of the numerous books to which reference is

made, and thus obtain, in many instances, more detailed information than it is practicable to include in a book of the character of the one here presented. While the facts described and discussed in the following pages were derived in many instances from personal observation, much is of necessity compiled from the writings of others. In all cases, I think, acknowledgments are made of the sources from which information has been borrowed. The numerous foot-notes inserted will enable the reader to verify the accuracy of those portions of the book which are essentially compilations.

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CHAPTER I

CHARACTERISTICS OF VOLCANOES

Both the historical and scientific interest in volcanoes originated in southern Europe. Etna, Vesuvius, Santorin, and the volcanoes of the Lipari islands, figure in Greek and Roman mythology, and have made a deep impression on the history and poetry of the Mediterranean region. These same volcanoes, in later times, lead to a scientific study of the phenomena attending volcanic eruptions. Although the same phenomena that attracted the attention of philosophers to the volcanoes of southern Europe have been manifested at hundreds of other localities, and many times on a far grander scale than even Pompeii has witnessed, yet on account of the length of time that observations have been carried on in the region referred to, and the painstaking accuracy of much of the work done there, it will long remain classic ground to the student of nature, as well as to the historian, the poet, and the painter.

Types of Volcanoes

In beginning the study of the volcanoes of North America, it is essential that we should learn at least the principal results attained in other regions respecting

the characteristics of volcanic eruptions. For th. as much space as is practicable under the plan above outlined, will be devoted at the beginning to the consideration of the volcanoes of southern Europe. Some attention will also be given to the volcanoes of Iceland, the Hawaiian islands, Japan, and the Java-Sumatra region.

Stromboli. — Rising from the Mediterranean, about sixteen miles northwest of the Strait of Messina, is a volcanic island known as Stromboli, one of the Lipari group. Its general form is that of an irregular four-sided pyramid. From an opening near its summit steam escapes almost constantly, and frequently with small explosions. The steam condenses so as to form a peculiar, fleecy cloud when illuminated by the sun, and glows at night with a ruddy light emanating from the highly heated and frequently molten rock within the opening, near the apex of the island. Owing to the long continued activity of the volcano, the light reflected at night from the cloud above its summit serves as a beacon to mariners, and has made it known as the Light-house of the Mediterranean.

The island of Stromboli is the exposed portion of a large volcanic pile, the base of which is deeply submerged. Its summit rises about 3000 feet above the sea, and soundings near at hand show that its base is submerged to about the same amount. Were the sea removed, it would stand as a precipitous, isolated mountain, rising from a plane to a height of 6000 feet, and with a base five or six miles in diameter. This mass of material has been forced out in a molten or plastic condition from an opening in the floor of the sea, and piled up about the vent. The tube or conduit, through

which the molten rock ascended, has been prolonged by the accumulation of the hardened lava about the original opening, and now leads to near the summit of the island. The conduit is still filled with molten lava derived from an unknown source, probably thousands of feet beneath the floor of the Mediterranean, and from time to time overflows, or explosions blow out fragments of plastic rock, and additions of fresh material are made to the pile. The position of the opening, through which molten rock, accompanied by great volumes of steam, escapes, is changed from time to time, although historical records that such is the case appear to be indefinite, and is now on the northwest side of the mountain, about one thousand feet below the summit. This opening is a cup-shaped depression, or *crater*. From it a flat slope, bounded on each side by steep cliffs, and known as the Sciarra, descends at an angle of about 35° to the sea. This steep slope, however, is a peculiar feature of Stromboli, and not characteristic of volcanoes in general.

The study of volcanoes has shown that they may, for convenience, be divided into two classes — the *explosive* and the *quiet* — with reference to the violence of their eruptions. Stromboli is an example of the former class, but is usually in a mild state of activity, and thus favorable for observing the characteristics of volcanic eruptions.

The nature of the eruptions usually in progress at Stromboli has been graphically described by Judd,[1] who visited the island in April, 1874, as follows:

[1] J. W. Judd, "Volcanoes," *International Scientific Series*. Appleton & Co., 1881. This book is recommended to students. From it much of the information presented in the present volume concerning the characteristics of volcanoes has been either directly or indirectly obtained.

"On reaching a point upon the side of the Sciarra, from which the crater was in full view before me, I witnessed and made a sketch of an outbreak which took place. [This sketch is reproduced in Fig. 1.] Before the outburst, numerous light curling wreaths of vapor were seen ascending from fissures on the sides and bottom of the crater. Suddenly, and without the slightest warning, a sound was heard like that produced when a locomotive blows off its steam; a great volume of watery vapor was

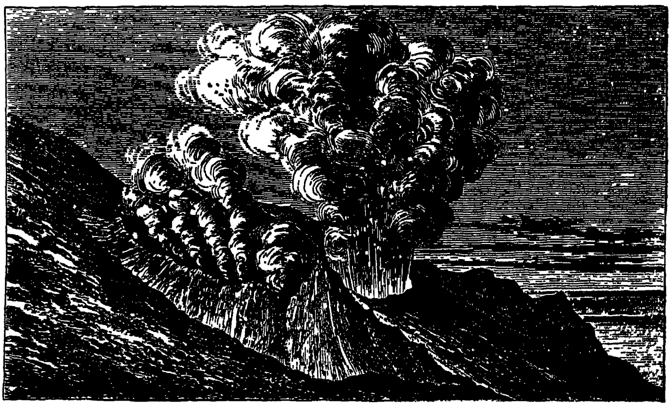


FIG. 1. The crater of Stromboli as viewed from the side of the Sciarra during an eruption on the morning of April 24, 1874. (After J. W. Judd.)

at the same time thrown violently into the atmosphere, and with it there were hurled upwards a number of dark fragments, which rose to a height of 400 or 500 feet above the crater, describing curves in their course, and then falling back upon the mountain. Most of the fragments tumbled into the crater with a loud, rattling noise, but some of them fell outside the crater, and a few rolled down the steep slope of the Sciarra into the sea. Some of these falling fragments were found to be still hot and glowing, and in a semi-molten condition, so that they

readily received the impression of a coin thrust into them."

From above the crater, when the direction of the wind is favorable, one can look down into the fiery caldron and learn more of the nature of the eruptions that take place. From such a point of view, as described by Judd, "The black, slaggy bottom of the crater is seen to be traversed by many fissures or cracks, from most of which curling jets of vapor issue quietly, and gradually mingle with and disappear in the atmosphere. But besides these smaller cracks at the bottom of the crater, several larger openings are seen, which vary in number and position at different periods; sometimes only one of these apertures is visible, at other times as many as six or seven, and the phenomena presented at these larger apertures are especially worthy of careful investigation.

"These larger openings, if we study the nature of the action taking place at them, may be divided into three classes. From those of the first class, steam is emitted with loud, snorting puffs, like those produced by a locomotive engine, but far less regular and rhythmical in their succession. In the second class of apertures masses of molten material are seen welling out, and, if the position of the aperture be favorable, flowing outside the crater; from this liquid molten mass steam is seen to escape, sometimes in considerable quantities. The openings of the third class present still more interesting appearances. Within the walls of the apertures a viscid or semi-liquid substance is seen slowly heaving up and down. As we watch the seething mass, the agitation within is observed to increase gradually, and at last a gigantic bubble is formed which violently bursts, when

a great rush of steam takes place, carrying fragments of the scum-like surface of the liquid high into the atmosphere.

"If we visit the crater by night, the appearances presented are found to be still more striking and suggestive. The smaller cracks and larger openings glow with a ruddy light. The liquid matter is seen to be red-hot or even white-hot, while the scum or crust which forms upon it is of a dull red color. Every time a bubble bursts and the crust is broken up by the escape of steam, a fresh, glowing surface of the incandescent material is exposed. If at these moments we look up at the vapor cloud covering the mountain, we shall at once understand the cause of the singular appearances presented by Stromboli when viewed from a distance at night, for the great masses of vapor are seen to be lit up with a vivid, ruddy glow, like that produced when an engine driver opens the door of the furnace and illuminates the stream of vapor issuing from the funnel of his locomotive."

The bursting of great bubbles of steam on the surface of the viscid lava within the crater accounts for the globular, fleece-like masses of vapor that give a special feature to the steam cloud seen above Stromboli. Similar concentric masses of vapor are a characteristic portion of the vapor columns that rise from many volcanoes during calm weather. An essential element, at least of the less violent eruptions of volcanoes, is thus shown to be the breaking of huge bubbles of steam.

The fact of special significance to be noted in the account of a mildly explosive volcanic eruption just cited, is that the throat of the volcano is filled with molten rock, portions of which are violently ejected from time to time by

the escape of steam which rises through the liquid lava. These fragments of semi-molten rock are hurled into the air and fall in part about the opening from which they were ejected, and build up a rim about it. A conical pile of this nature with an opening in its summit, is termed a *cinder cone*. We also note that sometimes the molten rock overflows the crater and descends the mountain as a lava stream. These features, as will be seen later, are characteristic of the eruptions of many volcanoes.

Although Stromboli is usually in a state of mild activity, yet occasionally the violence of its explosions is greatly increased. The roar of the escaping steam may then be heard for many miles; fragments of plastic rock are hurled thousands of feet into the atmosphere, and scattered not only over the entire island, but fall in the surrounding waters; and streams of molten rock flow down from the crater into the sea.

Vesuvius. — This world-famed volcano, situated near the shore of the Bay of Naples and about ten miles eastward of the city of Naples, is a charming and most beautiful object when beheld from afar. The first evidence of its presence that usually meets the gaze of the expectant traveller, whether approaching over the blue sea or through the picturesque land, is a vast column of steam, rising tranquilly far above the mountain's summit, and then expanding into a broad, vapory canopy. When the wind is not too strong, the cloud is seen to be made up of concentric, fleecy masses, each one of which, as in the case of the cloud above Stromboli, is due to the explosion of a great steam bubble in the caldron of molten rock from which it rose. The vertical shaft of steam with its expanded summit resembles in general form the outlines

of the characteristic stone pine of Italy, and for this reason is widely known as the *pine tree of Vesuvius*.

Vesuvius is a conical mountain about 4000 feet high. From the Bay of Naples the steep conical summit is seen to rise within the truncated and half-destroyed crater of an older and much larger volcano, the highest portion of which has an elevation of 3730 feet. The portion of the rim of the older crater still remaining is termed Mt. Somma.

Previous to the Christian era, Vesuvius was familiar to the Romans as a conical mountain with a truncated summit, in which there was a deep depression some three miles in diameter. From the earliest historic times to the year 79, the volcano was dormant and its crater cold and overgrown with vegetation. In the year mentioned, an explosion of remarkable violence occurred, which blew away a large portion of the ancient crater and buried Pompeii and Herculaneum beneath the fragmental products that were ejected. It was during this eruption that Pliny lost his life, while making observations on the earliest volcanic explosion of which history retains a definite record.[1] A portion of the wall of the ancient crater, referred to above as Mt. Somma, was left, and within its embrace the modern Vesuvius has been built.

The volcano, which gives a matchless charm to a thousand picturesque vistas in the vicinity of Naples, has, like Stromboli, its periods of mild activity, interrupted at irregular intervals by explosive eruptions of great violence, which, in many instances, are accompanied

[1] This tragic event was minutely and graphically recorded by Gaius Plinius, the younger Pliny. A translation of this account may be found in Shaler's "Aspects of the Earth." New York, 1889, pp. 50–56.

by overflows of lava. Unlike Stromboli, however, the variations in its activity are strongly pronounced. At times Vesuvius is dormant for many years and even for centuries, and again awakens to an activity of such energy that southern Italy is shaken by earthquakes, steam escapes in explosions so violent as to hurl stone and dust high in the air, and even blow away and distribute far and wide over the adjacent region the material previously forming the summit of the mountain. While Stromboli since the dawn of history has been in a state of mild activity, interrupted at long intervals by explosions of greater violence, Vesuvius has been alternately dormant and its summit cold, and again an object of dread which has brought destruction and death to the fair land surrounding it. These two volcanoes belong to the explosive type, as the student will appreciate more fully in advance, but illustrate two quite well marked phases of that type, which have been recognized also in many other volcanoes, and are termed the *Strombolian stage* and the *Vesuvian stage*,—the former characterized by long-continued but mild activity, the second by periods of rest broken by explosions of extreme violence.

When Vesuvius is in a mild state of activity, approaching that normal to Stromboli, one may safely climb to the edge of the great bowl which usually exists at the summit and even descend into it, and observe the nature of the molten rock that rises from below, the manner in which the steam escapes from its enclosing magma, etc.

In November, 1879, I climbed the cone composed of loose fragments of lava, forming the summit portion of Vesuvius, and reached the rim of the bowl-shaped depression at the summit. The crater near the summit then

had an outer slope of about 35°; the inner slope was more precipitous, and exposed the edges of outward-dipping layers of fragmental material, showing that the opening had not long previously been enlarged by the blowing away of the inner portion of its rim. This occurred perhaps during the energetic eruption of 1872. The crater was by eye measurement 150 to 200 feet deep, and a thousand feet in diameter. It was floored with black, slag-like lava. The lava in many places was wrinkled or corrugated, owing to slow movement before cooling, and intersected by numerous fissures through which the glowing, red-hot rocks beneath could be plainly seen. From some of the fissures, steam was escaping with a hissing noise. In the central portion of the floor of hardened lava, and resting on it, was a rough, conical pile of slag-like lava, rising to a height nearly as great as the highest point on the encircling rim. This inner pile was the *cone of eruption*. From its summit great volumes of vapor were rolling out, accompanied by puffs which sent globular masses of steam high in the air. With each puff, stones four or five inches in diameter and highly heated, were hurled to a height of between one and two hundred feet in the air. Some of the stones fell on the sides of the conical pile, and occasionally one would roll to its base. At each explosion the entire crater vibrated, but not sufficiently to be at all alarming. I descended to the floor of the crater, and could walk with safety over the recently congealed lava, although it was hot to the feet. One could easily thrust a walking-stick through the crevices and into the still semi-molten lava beneath. On gaining the base of the cone of eruption, I clambered about half-way up its rough sides, but, as the wind was

not strong or regular in any one direction, the stones hurled into the air at each explosion fell all about the central orifice, while the steam and gases became more and more dense near the summit. The pulsating and rumbling of the molten material within the crater could be distinctly heard, and the trembling of the rocks at each explosion when a belch of steam occurred, made it troublesome to stand erect. Although prevented from seeing the actual boiling of the lava within the crater, this omission can be supplied by observations made by N. S. Shaler,[1] in the winter of 1882:

"Taking advantage of a strong gale from the north, the well-known *tramontana* of Italy, it was possible to creep up to the very edge of the crater and look down upon the surface of the boiling lava, from which the gases were breaking forth. Although the pit was from time to time filled with whirling vapor, the favoring wind often swept it away so that for a few seconds it was possible to see every feature of the terrifying scene. Several times a minute the surface of the tossed lava was rent by a violent explosion of gases, which appeared to hurl the whole mass of fluid rock into the air. The ascending column of vapor and lava fragments rose as a shaft to a height of several hundred feet. Many of the masses, which seemed to rise with the ease of bubbles, were some feet in diameter, and made a great din as they crushed down upon the surface on the southward side of the crater. They often could be seen to fly into fragments as they ascended. At the moment of the explosion the escaping gases appeared transparent, a few score feet above the point of escape the ejected column became of a

[1] "Aspects of the Earth." New York, 1889. pp. 62–64.

steel-gray color, and a little higher it changed to the characteristic hue of steam. That it was steam slightly mixed with other gases was evident whenever in its whirling movements the vaporous column swept around the point of observation. The curious "work-day odor" of steam was perfectly apparent, together with the pungent sense of sulphurous fumes suggestive of an infernal laundry.

"Although the heat at the moment of explosion was great, it was possible, with the shelter to the face secured by an extemporized mask, to avoid any serious consequences from it, and even to make some rather rude and unsatisfactory diagrams of the scene. The principal obstacle to observation arose from the violence of the shocks given to the cone and propagated through the air by the explosions, which made it extremely difficult to fix the attention on the phenomena. . . .

"As if to complete the illustration of volcanic phenomena which this little outbreak afforded, there was a small rivulet of lava pouring from the low wall of cinders on one side of the cone and flowing quietly down the slope. It was not much larger than the stream of liquid iron which flows from an iron-furnace to the moulds which await it, but in the motion all the essential features of the greatest of these fiery torrents could be seen. The surface of the fluid, cooled in the air, slowly hardened into a viscid scum. This scum, urged forward by the swifter movement of the more fluid matter below, was wrinkled as is the cream on a pan of milk when it is slowly poured over the edge of the vessel."

Two of the most important phases of volcanic eruptions are illustrated by the observations just cited; one the

blowing out of rock fragments by steam explosions, the other the overflow of molten rock. These are the chief manifestations, with the exception of the escape of vast volumes of steam, that attract the attention in all volcanic eruptions, and may occur separately or be united in the same outbreak.

The mild explosions and rivulets of lava characteristic of the eruptions of Stromboli and of the more subdued phases of Vesuvius when in action, have but to be increased in intensity and volume, to enable one to appreciate the nature of even the most stupendous volcanic outbreak that the world has ever witnessed. The proximate cause of the explosions in the eruptions described above is plainly the expansive energy of steam. The origin of the steam, the cause of the pressure on the molten rock which forces it upward, and the source of the heat that liquefies the lava, will be considered in advance.

Vesuvius, as already stated, was dormant from its first mention in history until the year 79 of the Christian era. Its grandest eruptions probably occurred in prehistoric times, since the ancient crater, of which Mt. Somma is a remnant, was of far greater magnitude than the modern Vesuvius. By restoring the curve of the portion of the ancient crater wall which remains, it may be shown that the Somma crater was fully three miles in diameter, and probably more lofty than the summit of the modern cone within it. The duration of the last prehistoric period of quiescence is unknown, but probably embraced several thousand years, since the floor of the crater was cold and solid, and overgrown with vegetation, previous to the eruption of 79. It was in this natural fortress that Spartacus and his band of gladiators took refuge.

Some of the features of the great eruption of 79 are recorded in the account given by the younger Pliny already referred to. He states that his uncle "was at Misenum [on the west side of the Bay of Naples, about twenty miles in a direct line from Vesuvius] and was in command of the fleet there. It was at one o'clock in the afternoon of the 24th of August that my mother called his attention to a cloud of unusual appearance and size. . . . A cloud was rising from one of the hills (it was not then clear which one, as the observers were looking from a distance, but it proved to be Vesuvius), which took the likeness of a stone-pine very nearly. It imitated the lofty trunk and the spreading branches, for, as I suppose, the smoke had been swept rapidly upward by a recent breeze and was then left hanging unsupported, or else it spread out laterally by its own weight and grew thinner. It changed color, sometimes looking white, and sometimes, when it carried up earth or ashes, dark and streaked." Leaving Misenum in his ships, Pliny the elder proceeded toward the head of the bay. "Ashes began to fall on his ships, thicker and hotter as they approached the land. Cinders and pumice, and also black fragments of rock cracked by heat, fell around them. The sea suddenly shoaled, and the shores were obstructed by masses from the mountain." An account of the death of Pliny, suffocated by gases from the volcano, then follows.

In another letter the younger Pliny describes his flight with his mother from Misenum. "It was now seven o'clock [on the morning of August 25], but the light was still faint and doubtful. The surrounding buildings had been badly shaken, and though we were in an open spot

[a little yard between his uncle's house and the sea], the space was so small that the danger of a catastrophe from falling walls was great and certain. Not till then did we make up our minds to go from the town. . . . When we were free from the buildings we stopped. There we saw many wonders and endured many terrors. The vehicles we had ordered to be brought out kept running backward and forward, though on level ground; and even when scotched with stones they would not keep still. Besides this, we saw the sea sucked down and, as it were, driven back by the earthquake. There can be no doubt that the shore had advanced on the sea, and many marine animals were left high and dry. On the other side was a dark and dreadful cloud, which was broken by zigzag and rapidly vibrating flashes of fire, and yawning showed long shapes of flame. These were like lightnings, only of greater extent. . . .

"Pretty soon the cloud began to descend over the earth and cover the sea. It enfolded Capreæ and hid also the promontory of Misenum." The flight was continued. "Ashes now fell, yet still in small amount. I looked back. A thick mist was close at our heels, which followed us, spreading out over the country, like an inundation." Turning from the road in order to avoid the fleeing, terror-stricken throng, they rested. "Hardly had we sat down when night was over us — not such a night as when there is no moon and clouds cover the sky, but such darkness as one finds in close-shut rooms. One heard the screams of women, the fretting cries of babes, the shouts of men. . . .

"Little by little it grew light again. We did not think it the light of day, but a proof that the fire was

coming nearer. It was indeed fire, but it stopped afaı off; and then there was darkness again, and again a rair of ashes, abundant and heavy, and again we rose anc shook them off, else we had been covered and ever crushed by the weight. . . . At last the murky vapoı rolled away, in disappearing smoke or fog. Soon the real daylight appeared; the sun shone out, of a lurid hue, to be sure, as in an eclipse. The whole world which met our frightened eyes was transformed. It was covered with ashes white as snow." Young Pliny and his mother returned to Misenum, and survived the perils to which they were exposed.

During this eruption Pompeii was buried beneath dust and "ashes," and its site obliterated and lost to memory for many centuries. Herculaneum, situated still nearer the mountain, was overwhelmed by similar material (light, gray, pumiceous lapilli), mixed with water and forming a mud which has since hardened like cement.

In the narrative just cited, there is no mention of lava having been seen flowing from the mountain. The eruption was caused by a stupendous outburst of steam, which disintegrated the lava that rose with it, and spread the fine fragments far and wide over southern Italy. The essential features of this vast exhibition of the pent-up energy of subterranean steam, may be witnessed to-day in the little explosions that characterize the Strombolian stage of numerous volcanoes.

Following the Plinian eruption Vesuvius became quiet once more, but whether the escape of steam completely ceased or not, is not definitely known. The next eruption of which some account is extant, occurred in the year 203. Again in 472 an eruption of paroxysmal violence

took place, which destroyed villages that had been built over the buried cities of Herculaneum and Pompeii, and ejected lapilli to so great a height that it fell as far from the mountain as Constantinople.[1]

During a period of nearly 600 years following, only three eruptions are recorded. These were in 512, 685, and 993. Similar paroxysms of violent activity separated by long periods of quiescence and of even total cessation of energy, have marked the behavior of Vesuvius to the present time. A summary of what is known concerning the changes the mountain has experienced during this long period may be found in Lobley's work just cited.

The importance of a knowledge of the behavior of Vesuvius to the inhabitants of the rich and populous region surrounding it, came at length to be fully appreciated. About thirty years since, an observatory was established on a western spur of the mountain, for the purpose of keeping a record of the behavior of the volcano, as well as of meteorological phenomena and earthquake disturbances. The Observatory since its opening has been in charge of Professor Luigi Palmieri, a well-known physicist of long experience. A special feature in the equipment of the Observatory is furnished by the instruments known as *seismographs*, for recording vibrations of the earth.

To Palmieri's skill as an observer, and the records of the instruments of the Observatory, and also to the application of photography in recording volcanic phenomena (Plate 2), we are indebted for the detailed

[1] J. L. Lobley, "Mount Vesuvius," London, 1889, pp. 101, 102. This book contains the most instructive description and history of Vesuvius accessible to the student.

history of the remarkable outbreak of Vesuvius in 1872.[1] A marked feature of this eruption was the pouring out of streams of molten rock or lava.

After being in a quiescent state from November, 1848, Vesuvius commenced to show signs of renewed activity in 1871, which continued, with moderate lava flows, for several months. Early in 1872, lava was poured out, some of the streams running for a week at a time. Following these more quiet discharges came a violent explosive eruption accompanied by voluminous lava streams, which culminated on April 26. The following account of this eruption has been compiled from Palmieri's report cited above:

On April 23 the Observatory instruments were agitated, the activity of the crater increased, and on the evening of the 24th lava streams descended the cone in various directions. All of these lava streams were nearly exhausted on the morning of the 25th; only one remaining, which issued from the base of the cone, not far from the spot where a similar stream had issued during the preceding month. During the succeeding night a party of students visited the scene of the disturbance. A cloud of smoke accompanied by a hail of hot projectiles enveloped them when they were close to the lava torrent, and eight of the party are known to have perished.

A fissure opened on the northwest side of the cone and extended into the depression known as Atria del Cavallo, which separates the modern cone of Vesuvius from the fragment of an ancient crater rim, named Mt. Somma. The length of this fissure was about 1800 feet. Lava

[1] "The Eruption of Vesuvius in 1872," by Professor Luigi Palmieri, with notes. Edited by Robert Mallet. London, 1873. pp. 81–102.

was poured out from its lower part, which extended into the Atria. Another fissure opened in the south side of the cone, but did not extend to its base, and also emitted a stream of lava. Streams of lava of less importance furrowed the cone in other directions, but the largest quantity came from the fissure first mentioned; the one in Atria del Cavallo. This lava stream was for some time restrained in the Atria, in holes and inequalities of a lava flow of the previous years, but these being filled, it divided into two branches; the smaller branch flowing toward Resina, near the site of buried Herculaneum, about five miles from Naples; the larger branch took a more westerly course, and precipitated itself into a valley, known as Fossa della Vetrana, occupied its whole width, about 2400 feet, having advanced nearly 4000 feet in three hours. This larger branch of the original stream again divided, and one branch partially overwhelmed the villages of Massa and St. Sebastiano, situated southwest of Vesuvius and about three and a half miles from its summit.

On the night of the 26th, the Observatory lay between two streams of molten lava, which emitted such an intense heat that the glass in the windows cracked and the smell of scorching was perceptible in the rooms.

The cone, besides being furrowed by the lava streams just described, was traversed by several others of smaller size and briefer duration. In fact, the summit of the mountain appeared perfectly perforated, and lava seemed to ooze through its whole surface. As expressed by Palmieri, "Vesuvius sweated fire." In the daytime the cone appeared momentarily covered with white steam jets (fumaroles) which looked like flakes of cotton against the

dark mountain side, appearing and disappearing at brief intervals.

Simultaneously with the grand fissuring of the cone, two large craters opened at the summit, discharging with a dreadful noise, audible at a great distance, an immense cloud of steam, dust, lapilli, and bombs. Volcanic bombs are masses of plastic lava hurled into the air by the outrushing steam and acquiring a spherical shape by reason of their rotation. The material thus projected into the air reached an elevation of nearly 4000 feet above the summit of the mountain. It has been computed that the initial velocity of these projectiles must have been in the neighborhood of 600 feet per second.

The igneous period of the eruption was short, for on the morning of the 27th the lava stream which flowed toward Resina, after covering a few cultivated fields, stopped; the lava descending from the summit of the mountain southward, toward Camaldoli, three miles and a half east of Resina, also ceased to flow; and the great lava torrent which passed the Observatory was lowered by the onward flow of its central portion, leaving the hardened sides standing like two parallel embankments.

The lava flows having ceased on the evening of the 27th, the dust, lapilli, and larger projectiles became a little more abundant, whilst the roaring noises of the craters apparently became greater. The pine-tree cloud that rose from the summit of the mountain was of a darker color, and was furrowed by lightning flashes which were visible by daylight from the Observatory, where the thunder that followed the flashes was heard usually after an interval of about seven seconds.

On the 28th the dust and lapilli continued to fall

abundantly, darkening the air, and the terrible noise, due largely to the steam escaping from the crater, continued with scarcely any diminution.

On the 29th, with a strong wind blowing from the east, scoria of such size fell at the Observatory, that the glass of the windows was broken. The noise from the crater continued, but the projectiles rose to a less height, indicating a diminution in the power of the eruption. Toward midnight the noise of the craters was no longer continuous, and recurred with less force and for shorter intervals. Almost at the same hour, a tempest burst over the region with loud thunder, but accompanied by little rain. The disasters so frequently occurring during the outbursts of Vesuvius, due to the heavy rains, which, mingling with the loose dust and lapilli, cause torrents of mud to sweep down the mountain's sides, thus, happily, were averted.

On the 30th the detonations from the crater were few, and the steam issued only at intervals. By the 1st of May the eruption was entirely over.

During the eruption earthquake shocks caused the Observatory to oscillate continuously, and were felt not only in the adjacent territory, but as far as Montovi.

The great quantity of lapilli which fell, buried the scoria composing the upper portion of the cone of Vesuvius and made the ascent to the summit difficult. Palmieri states that having reached the top, he found a large crater divided into two parts by what seemed a cyclopean wall. The two abysses had vertical sides, and revealed the fact that the cone was composed of alternating beds of scorial and compact lava. The vertical depth of the craters was approximately 750 feet.

A remarkable feature of the eruption, and one that has been observed in a few other instances, was that not only the cone of Vesuvius, but the whole adjacent country appeared white for many days as if snow-covered. This was due to the common salt contained in the dust and lapilli with which the region about the mountain was strewn.

The amount of molten rock outpoured during this eruption covers an area of about one and eight-tenths square miles, with an estimated average depth of thirteen feet. Of the amount of dust and lapilli scattered far and wide and of the volume of steam and other gases discharged, not even an approximate estimate can be made.

From the account just given, it will be seen that one of the most important features of a volcanic eruption is the transfer of material in a solid, liquid, or gaseous form, from deep below the surface of the earth to its exterior. Whence the heat that liquefied the lava, and whence the force that raised it to the surface?

The history of Vesuvius shows that it is characterized by alternating periods of repose and of activity; the former being measured by years and even centuries, the latter by days and even hours. The long periods of mild activity similar in character to the normal condition of Stromboli, or of complete inactivity when the mountain summit is cold and silent, are broken by explosive paroxysms of which the eruptions of 79 and 1872 are illustrative. The great majority of the volcanoes of the world belong to the Vesuvian type.

Krakatoa. — While Vesuvius by reason of its long history and the care with which it has been studied, is taken as the type of explosive volcanoes, its most disas-

trous eruptions sink into comparative insignificance beside the mighty explosion that occurred in a volcano known as Krakatoa, in 1883.[1] Krakatoa is situated on an island of the same name in the Strait of Sunda, between Java and Sumatra.

The eruption of Krakatoa was the most appalling outbreak of its kind that has occurred in modern times, and, although of the same general character as the eruptions characteristic of Stromboli and Vesuvius, was so tremendous, and its effects so disastrous and so wide-reaching, that it is difficult, if not impossible, for one to form a conception of what took place.

Like Vesuvius previous to the great eruption of 79, Krakatoa was dormant and overgrown with vegetation, when the now memorable explosion occurred. Previous to the eruption, the island of Krakatoa was occupied by three mountain groups; the highest summit, that known as Krakatoa, being 2622 feet above the sea. All of these mountains were of volcanic origin, and bore evidence of the occurrence of vast explosive eruptions in prehistoric times. The only known outbreak previous to the one described below, took place in 1680.

The eruption of 1883 consisted of a series of violent explosions which occurred from August 26 to 28, the most formidable being about seven on the morning of the 27th. This was the grand culmination of a series of minor explosions accompanied by earthquakes, which began four months previously, on the morning of May 30. The noise of these premonitory disturbances was heard at

[1] A detailed report of this eruption by a committee of the Royal Society has been published with the title, "The Eruption of Krakatoa, and Subsequent Phenomena," by Trüber & Co., London, 1888. A quarto volume of 494 pages and numerous maps and plates.

Batavia and other points more than a hundred miles from the scene of the outbreak. It became known to the inhabitants of Java and Sumatra that an eruption of marked violence was in progress on the island of Krakatoa, but it was not until Sunday, August 26, that the demonstrations became alarming. A little after noon on that day, a rumbling noise, accompanied by short, feeble reports, was heard at Batavia, 100 miles east of Krakatoa, and at other localities equally distant. Those sounds increased during the night, and at seven the next morning there came the most appalling crash of all. The sky over the Strait of Sunda and the bordering coasts became darkened by the vapor and dust blew into the air, and the darkness increased until the blackness of midnight ensued. Showers of dust began to fall. Repeated earthquakes occurred, and loud explosions, like the discharge of heavy guns, were heard the almost incredible distance of 2267 miles from the scene of action.

One of the nearest witnesses of the eruption was Captain Watson, commander of the British vessel, *Charles Bal*, which was ten miles south of the island of Krakatoa on the Sunday afternoon when the volcano entered on its greatest series of paroxysms. The island was shrouded in a vast black cloud, and sounds like the discharge of heavy guns were heard at intervals of a second of time, and accompanied by a crackling noise thought to have been due to the colliding of rock fragments in the air. A rain of pumice, the larger pieces still quite warm, fell on the ship.

It has been estimated that the column of steam, dust, and lapilli that rose above Krakatoa, corresponding with the pine tree of Vesuvius, attained a height of from

twelve to seventeen miles, and by some observers was estimated to have been twenty-three miles in altitude. From its widely expanded summit a rain of dust, lapilli, and fragments of pumice descended on the sea and islands over a radius of scores of miles. The finer particles blown into the upper regions of the atmosphere were borne away by air currents and finally distributed over the surface of the entire earth. The vast quantities of fine dust blown into the upper regions of the atmosphere caused the magnificent sunset and sunrise effects that were witnessed on every continent for two or three years after the eruption.

Observers who saw the magnificent spectacle from a distance describe the towering column of steam, dust, and lapilli, as being momentarily illuminated by lightning flashes. The thunder that followed these discharges was lost in the roar produced by the escaping steam. At night, the canopy illuminated by the light of the volcano "resembled a blood-red curtain with edges of all shades of yellow; the whole of a murky tinge, through which gleamed fierce flashes of lightning."

The force of the explosion within the crater of Krakatoa was such as to blow away half of the mountain and a large portion of the island on which it stood. At a locality in the central part of the island where a mountain rose previous to the eruption, soundings now show a depth of a thousand feet of water. The geography of the island was thus greatly changed, much of the material of which it was composed being blown away.

There is no room for doubting that the eruption of Krakatoa was of essentially the same nature as the less violent explosions of Vesuvius and Stromboli. That is,

the immediate or proximate cause of the explosion and of all its attending phenomena was the escape of superheated steam, or the ignition of gases produced by the disassociation of the elements of water. The suddenness and violence with which the steam escaped may be appreciated to some extent, by the general account of the eruption given above, but will be better understood by citing more detailed observations. As in all explosions, vibrations, or waves, were generated in the surrounding media. In the case of Krakatoa these were of three classes: (1) atmospheric waves, (2) sound waves, and (3) water waves.

1. The atmospheric waves: A large number of barometric observations in various parts of the world have shown that the atmospheric wave generated by the great explosion on the morning of August 27 expanded in all directions until it became a great circle, 180° distant from the scene of the explosion, and then contracted to a node at the antipode of its place of origin; it then expanded and travelled back about the earth to Krakatoa; whence it again started on a journey around the world; again returning and again expanding and returning, expanding outward from its starting-point still again, it travelled half around the earth once more before its amplitude became so reduced that it ceased to make a distinct record on self-recording barometers. This remarkable phenomenon of an atmospheric wave travelling about the entire earth was repeated three and a half times. The time required for each complete excursion around the earth was thirty-six hours and from twenty-five to fifty minutes.

2. The sound wave: Sounds like the discharge of

heavy guns in quick succession accompanied the eruption of Krakatoa, and were heard, as already stated, at places more than 2000 miles distant. Among the numerous accounts showing the immense area over which the sound waves travelled, published by the Committee of the Royal Society, are the following:

At the Port of Acheen, at the northern extremity of Sumatra, distant 1073 miles, reports like the discharge of cannon at sea were heard, and the troops were put under arms.

At Singapore, distant 522 miles, two steamers were despatched to look for the vessel which was supposed to be firing signal guns.

At Bangkok, in Siam, distant 1413 miles, the sound was heard; and also at Labuan, in Borneo, distant 1037 miles.

The discharges were also noted at places in the Philippine islands, 1450 miles away.

The localities just mentioned lie to the northward of Krakatoa. In the opposite direction the noise was heard at Perth, 1092 miles distant, sounding like guns fired at sea, and at Victoria Plains, 1700 miles, in western Australia; and Alece Springs, 2233 miles, in southern Australia.

In a westerly direction, the sounds were heard at Dutch Bay, Ceylon, 2058 miles; and at the Chagoz islands, 2267 miles. The last named locality is the farthest from Krakatoa at which the sounds were noted.

Some idea of the immense distances over which the sound waves travelled may be obtained by a comparison with distances in North America. Had the noise produced by the earthquake that shook Charleston, South Caro-

lina, August 31, 1886, been as loud as those which accompanied the explosion of Krakatoa, — and the atmospheric and other conditions favoring transmission been the same, — it might have been heard at Los Angeles, California, and on the Prince Edward islands.

3. The water wave: The eruption at Krakatoa, it will be remembered, occurred on a small island, and was in part subterranean. A shock was transmitted to the water of the sea, which caused it to rise and roll away in great waves. The largest of these sea waves, on reaching the shores of Sumatra and Java, rose to a height of fifty feet above the normal water-level and caused immense losses of life and property.[1] The records of self-registering tide-gauges in various countries show that the waves thus started travelled at least half around the globe.

The brief summary of the character and effects of the eruption in the Strait of Sunda will, I fancy, incline the reader to agree with one of our most profound students of volcanic phenomena, who remarks that, while Vesuvius is regarded as a very obstreperous volcanic vent, its performances are mere Fourth of July fireworks in comparison with the Day of Judgment proceedings of Krakatoa.

If space permitted, a long series of explosive volcanic eruptions might be described, connecting the mild discharges of Stromboli, which can be watched with safety at a distance of a few rods, with that of Krakatoa, the effects of which in one form or another were felt over

[1] It is stated by R. D. M. Verbeek, in a report on the eruption of Krakatoa, published by order of the Governor-General of the Netherland Indies, in 1886, that 36,380 human beings, including 37 Europeans, perished, the greater part of whom were destroyed by the sea waves; 163 villages were entirely, and 132 partially, destroyed.

the entire earth. The essential features in each instance would be the same; the striking differences being in the degree of violence that characterized the eruptions. The mild explosions of Stromboli and Vesuvius, as we have seen, are due to the escape of the superheated steam. The same agency (with probably the added effects of the ignition of oxygen and hydrogen, as will be considered later) can be accepted as the immediate or proximate cause of the disastrous explosion in the Strait of Sunda.

On a previous page it was stated that volcanoes could be conveniently divided into two classes,—those that are subject to explosive eruptions and those which discharge their lavas quietly. Let us see what illustrations are available of extrusions of molten rock from openings in the earth's crust, which are unaccompanied by the pyrotechnic displays characteristic of Vesuvius, Etna, Santorin, Teneriffe, Cotopaxi, Chimborazo, Conseguina, Jorullo, Orizaba, Fusiyama, Sumbawa, and many more—for the volcanoes of the explosive type far outnumber all others—of the world's most famous volcanoes.

Volcanoes of the Hawaiian Islands.—With the exception of small deposits of coral sand, etc., the Hawaiian islands are composed of rocks that were poured out in a molten condition from the earth's interior and piled up during successive eruptions, until the highest summit reached an elevation of nearly 14,000 feet above the sea. The islands rise from a deep sea. The base of the volcanic pile on the sea-floor is from 15,000 to 18,000 feet below the ocean's surface. Could waters of the sea be withdrawn, the greatest of these volcanoes, Mauna Loa, would stand as a mountain fully 30,000 feet high, and

even exceed the elevation of the loftiest summit of the Himalaya Mountains above the present sea level.[1]

The Hawaiian group consists of four larger and four smaller islands. The largest and most easterly of the group, and the only one on which active volcanoes occur, is Hawaii, which is about ninety miles long by seventy miles wide, and has an area of approximately 4000 square miles.

One of the most graphic accounts of the Hawaiian volcanoes, and the one best suited to the present discussion, is in a published lecture on the "Hawaiian Islands and People" by C. E. Dutton.[2] Much of what follows concerning the volcanoes referred to is derived from this interesting pamphlet.

On the Island of Hawaii there are four great volcanoes, and many smaller craters which are now dormant. The southern half of the island is occupied by two grand volcanoes, Mauna Loa and Kilauea. The great central pile is Mauna Loa, the monarch among modern volcanoes. No other in the world approaches it in the vastness of its mass or in the magnitude of its eruptive activity. Etna and all its adjuncts are vastly inferior; while the three great volcanic cones of the Pacific coast of America,—Shasta, Hood, and Rainier,—if melted down and run together into one pile, would still fall much below the volume of the island volcano.

[1] Many accounts of the Hawaiian volcanoes have been published; among those most easily accessible to American students are: "Hawaiian Volcanoes" by C. E. Dutton, in the U. S. Geological Survey, 4th Annual Report, 1882–83; and "Characteristics of Volcanoes" by J. D. Dana, New York, 1890. The latter contains many references to earlier publications.

[2] A lecture delivered at the U. S. National Museum, Feb. 9, 1884 (separately published), Washington, 1884.

The summit of Mauna Loa is a moderately flat plain five and a half miles long and nearly four miles wide. Within this plain is sunken a pit three miles long, two miles wide, and a thousand feet deep. In the floor of this pit, at certain times, may be seen a lake of red-hot, liquid lava, varying in size from time to time, but occasionally as large as thirty or forty acres. At intervals of fifteen or twenty minutes a column of liquid lava of great brilliancy is shot upwards, fountain-like, to a height of over five hundred feet, and falls back into the lava lake in a fiery spray. This grand display is sometimes kept up for months, and is generally terminated by an eruption. When an outbreak occurs it does not usually take place at the summit, but a fissure suddenly opens in the side of the mountain, out of which a sheet of lava spouts hundreds of feet into the air, and falling, collects into a river of fire half a mile in width. When this occurs, the lava lake in the crater subsides, and a vast cavity is left, into which masses of rock from the sides, previously supported by the liquid lava, break away and are precipitated with great commotion. This river of molten rock rushed at first with great velocity down the side of the mountain. After running some miles it reaches more level ground, when it spreads out in great lakes or fields, and its surface becomes blackened as it cools and hardens. These great eruptions take place without explosions such as characterize the outbursts of Vesuvius, but the lava flows quietly out in enormous deluges, running sometimes for months, or even a whole year, with only the least possible signs of explosive action throughout the entire duration of the flow. Rarely are the eruptions accompanied by earthquakes. So mild are the discharges that an observer

may stand to the windward of one of the fiery fountains, and so near that the heat will make his face tingle, yet without danger. Usually the outbreaks take place without warning, and even without the knowledge of the people in the vicinity, who first become aware of them at night, when the whole heavens are aglow with the reflected light.

The great lava streams that flow down the side of Mauna Loa sometimes attain a length of nearly fifty miles, and occasionally enter the sea. The low angle of slope presented by the flanks of the mountain, and its nearly flat summit, are due to the tendency of the sheet of liquid rock to travel far and spread widely before cooling. It is by the successive addition of such sheets that the mountain has been built up. Nothing like the bombs, scoria, lapilli, and ashes, that are piled about the orifices of volcanoes of the explosive type, occur. The molten rock is characterized by its liquidity. It does not retain the occluded steam until a state of extreme tension and ultimate violent explosion is reached.

After mighty Mauna Loa, the next most interesting volcano on Hawaii is Kilauea, situated about twenty-five miles to the eastward and rising only 4200 feet above the sea. In the moderately flat summit of Kilauea there is a pit or crater, about three and a half miles in length and two and a half miles in width, nearly elliptical in plan and surrounded with cliffs from 300 to 700 feet high. A view of the interior of this crater as it appeared in the summer of 1883 is described by Dutton, as follows: [1]

"The object upon which the attention is instantly fixed

[1] "Hawaiian Volcanoes," U. S. Geological Survey, 4th Annual Report, 1882–83, pp. 104, 106.

is a large chaotic pile of rocks situated in the centre of the amphitheatre, rising to a height which by an eye estimate appears to be about 350 to 400 feet. From innumerable places in this mass volumes of steam are pouring forth and borne to the leeward by the trade wind. This pile of lava blocks is really a cone of eruption with a small crater at the top. At one side of its base is an opening in the floor of the main crater, within which one beholds the ruddy glow of boiling lava. From numerous points in the surrounding floor of the vast amphitheatre clouds of steam issue forth and melt away in the steady flow of the wind. The scene within the great basin is desolate and forbidding in the extreme, but upon the summit of the encircling walls, and over the outer slopes of the mountain, there is a wealth of luxuriant tropical vegetation."

Descending the crater walls and crossing the floor of recently hardened lava, from which steam is issuing through countless fissures, one may gain the border of the inner basin and look down on the surface of the pool of molten rock that it holds. It is to be remembered that this pool is really the summit of a column of liquid rock which descends for thousands of feet into the earth. Although red hot and molten at the top, the heat increases with the depth. Bubbles of steam are continually rising through the fluid mass and escaping from its surface. As described by Dutton, this pool is about 480 feet long and a little over 300 feet in width. "Its shape is reniform, and all about it rise vertical walls fifteen or twenty feet high. When one first reaches it the probabilities are that the surface of the lake will be coated over with a black solidified crust, showing a rim of fire all about its

edge. At numerous points at the edge of the crust jets of fire are seen shooting upward, throwing up a spray of glowing lava drops and emitting a dull, simmering sound. The heat for the time being is not intense. Now and then a fountain breaks out in the middle of the lake and boils feebly for a few minutes. It then becomes quiet, but only to renew the operation at some other point. Gradually the spurting and fretting at the edge augments. A belch of lava is thrown up here and there to the height of five or six feet and falls back upon the crust. Presently near the edge a cake of the crust cracks off, and one edge of it bending downward descends beneath the lava, and the whole cake disappears, disclosing a naked surface of liquid fire. Again it coats over and turns black. This operation is repeated at other points on the border of the lake. Suddenly a network of cracks shoots through the entire crust. Piece after piece of it turns its edge upward and sinks with a grand commotion, leaving the whole pool a single expanse of liquid lava. The lake surges feebly for a while, but soon comes to rest. The heat is now insupportable, and for a time it is necessary to withdraw from the immediate brink. Gradually the surface darkens with the formation of a new crust, which grows blacker and blacker until the last ray of incandescence disappears. This alternation of the freezing of the surface of the lake and the breaking up and sinking of the crust goes on in a continuous round, with an approach to a regular period of about two hours."

For a more extended account of the quiet eruptions characteristic of the Hawaiian volcanoes, I shall, for want of space, be obliged to refer the reader to the highly instructive reports concerning them already referred to.

To understand the proximate cause of the boiling of the lakes of molten rock in the summits of the volcanoes of Hawaii, the escape of steam from them, the formation of jets and fountains of fluid lava, etc., it is of interest to recall a homely comparison suggested by Judd.

If a tall narrow vessel is filled with porridge or some similar substance of imperfect fluidity, and placed over a fire, the essential features of an eruption of Stromboli or of the boiling of the fiery lakes of Hawaii may be imitated in miniature. As the temperature of the mass rises, steam is generated within it, and in the efforts of the steam to escape, the substance is set in violent movement. The movements of the mass are partly rotary and partly vertical in their direction; as fresh steam is generated in the mass its surface is gradually raised, while an escape of the steam is immediately followed by a fall of the surface. An up and down movement is thus maintained, but as the generation of steam goes on faster than it can escape through the viscid mass, there is a constant tendency of the latter to rise toward the mouth of the vessel. At last, if heat continues to be applied to the vessel, the fluid contents will be forced up to its edge and flow over, the steam being suddenly and violently liberated from the bubbles on the surface of the mass, and a considerable quantity of the material forcibly expelled from the vessel. A stream of lava and the hurling of fragments of liquid or plastic rock into the air, as frequently happens in Stromboli and Vesuvius, or the spouting of fiery spray from the lava lakes of Hawaii, are thus imitated. The reason for the violent escape of bubbles of steam from the surface of boiling mush, or at the top of the conduit of a volcano, is apparent when it is remembered that the

source of heat is deep below the surface. Steam is also generated below the surface, but probably at a moderate depth, and is under the pressure of the liquid mass above, and, besides, the viscid consistency of the material tends to prevent the bubbles of steam from rising. But when the pressure is relieved by an overflow or by the bursting of surface bubbles, the steam below has greater freedom of escape, and rushes violently upward.

The cause of the explosions that occur in volcanoes of the Vesuvian type, and the spouting of lava fountains in the lava lakes of Hawaii, is the steam and gases contained in the molten material; the variations in the behavior of the fluid magma in these contrasted instances depend on variations in its consistency. Lavas that are sufficiently heated are fluid, and boil without explosions; when less highly heated they are cohesive, and boil less freely. Lavas are also of different composition; some melt more readily than others, and are more fluid at the same temperature. Lavas which consolidate quickly on a lowering of temperature stiffen at the surface, and by resisting the expansive force of the steam, which increases as it nears the surface, are ruptured violently and blown to fragments, while lava that does not stiffen so readily retains its fluidity and allows the steam to escape quietly.

Although it is not difficult to understand the conditions that are immediately associated with volcanic outbursts, the ultimate cause of the heat present, the nature of the force which causes the lava to rise from far below the surface, and the sources of the water that furnishes the steam are more obscure phenomena, which will be considered in advance.

Fissure Eruptions. — There is good evidence that most

volcanic eruptions originate along fissures in the earth's crust. The formation of cracks and fissures seems to be the cause of many of the earthquakes that precede the birth of new volcanoes, and also herald the renewal of activity in vents that have been dormant.

The study of faults, fissure veins, etc., has shown that fissures in the rocks are usually irregular and frequently intersect, thus admitting of the escape of steam and lava with greater facility at certain localities than at others. In some instances, too, volcanoes seem to be located where two fissures cross or intersect. An eruption once started tends to keep its conduit open, both on account of the pressure which causes the magma to rise, and the fusion of the walls with which the ascending lava comes in contact; but when a conduit becomes closed, other openings are frequently formed along the line of the original fissure. This is indicated in numerous instances where successive eruptions have occurred along a well-defined line or narrow belt. A linear arrangement of volcanoes has been recognized in many portions of the earth. An instance of this nature is illustrated on Plate 8, which represents a group of beautiful lapilli cones, and small lava flows, situated near Mono Lake, California. If this map were extended toward the northwest and southeast, other volcanoes along the eastern base of the Sierra Nevada would be included, which indicates still more clearly the intimate association of eruptions with a belt of compound fractures and faults.

Again, the sides of great volcanic mountains, like Etna, are frequently broken by radiating cracks, through which lava escapes with the formation of secondary craters and surface sheets of molten rock. The lava cooling and

hardening, in such fractures, forms more or less vertical sheets or dikes, which frequently stand in bold relief as weathering progresses.

Should the fissures through which molten rock reaches the surface in what may be termed normal volcanic discharge, become more widely opened or more numerous, it is evident that the outpouring of lava might occur more generally throughout their length. If the lava was highly liquid, it would spread out over the land in sheets, without building up craters and mountains, as happens when the energy of the confined forces finds relief at a single circumscribed locality. Such an outpouring of liquid rock would perhaps be the culminating phase of a series of volcanic outbreaks of less intensity, but would differ from them in its wider extent and in the character of the topographic changes produced, but not in its essential characteristics.

Great inundations of lava of the nature just considered are known to have occurred, and are designated as *fissure eruptions*.

If we imagine quiet eruptions of highly liquid lava, like those that have formed the broad, flat-topped mountains of the Hawaiian islands, to be increased many thousands of times in volume, and to have reached the surface through intersecting fissures having an aggregate length of several hundred miles, the liquid rock spreading in widely extended sheets over the country, filling the valleys and giving a new topography to the land, we will have what appears to be the most truthful conception of the leading characteristics of fissure eruptions. If, after one great sheet of lava has cooled and hardened, and its surface becomes covered with soil and vegetation, or

occupied in part by lakes, and dissected by streams, we imagine the fissures to be again opened and to break through the first formed layer, a second sheet of lava might be spread out over the previous one, covering its eroded surface, and burying the lacustral and other deposits that had been laid down on it during the interval of repose. Such a conception furnishes a mental picture of what observations show has taken place many times in certain large areas of the earth.

No examples of fissure eruptions of the nature outlined above, can be cited as having taken place in historic times, unless some of the great lava flows of Iceland may be considered as comparatively small illustrations of this method of extrusion. At least two series of widely spread lava sheets of ancient date, however, can be shown to have originated in this manner. One of these occurs in the northwestern portion of the United States, and has been named the *Columbia lava;* the other, of about the same extent, is in India, and is known as the *Deccan trap.*

The Columbia lava covers an area of between 200,000 and 250,000 square miles in Idaho, Oregon, Washington, and northern California, and is composed of numerous sheets, some of which are separated by lacustral sediments of Tertiary age, and has a maximum thickness of over 4000 feet. A summary of what is known concerning this, the greatest of all the volcanic eruptions of North America, will be presented in a succeeding chapter. A counterpart of nearly all its characteristic features occurs in India.

The Deccan Trap. — On the west side of the peninsula of India there is a region about 200,000 square miles in area, where the surface rocks are basalt. Bombay is

situated in the central portion of the western or seaward margin of this immense tract.

The Deccan trap differs from the Columbia lava in age, being older, and belonging to the Cretaceous instead of the Tertiary period. It also differs from the similar area in America, in the fact that the various sheets of which it is composed have been but slightly disturbed from their original horizontal position. The Columbia lava, as will be explained in advance, has been broken throughout extensive areas by many lines of fracture, and the blocks thus produced tilted and their edges upturned so as to form mountain ranges.

The Deccan trap, for the most part, has never been covered by later formations, but on account of the great length of time it has been exposed, and also because of the warm and humid climate of India, it has suffered deep decay, and is covered quite generally with a thick layer of residual earth known as *laterite*.

In the vicinity of Bombay, the Deccan trap has a thickness of over 6000 feet, but thins out gradually eastward. The western portion of the area is covered by the sea, so that its full extent is unknown. In the southern prolongation of the trap area, its thickness is estimated at from 2000 to 2500 feet; in the extreme eastern portion, between 500 and 600 miles eastward of Bombay, the thickness in general is but 500 feet. The average thickness for the entire area is thought to be about 2000 feet.

The Deccan trap is a dark basalt and consists of many layers, some of which are separated by sheets of lacustral sediment, and by volcanic lapilli and "ashes." Where the rocks beneath the basalt are exposed, they are

found to be traversed by dikes. On the surface of the basalt there are no volcanic cones or craters of any description, which can be considered as marking the positions of vents from which the lava was extruded.

In all of these respects the vast lava-covered area of India agrees, almost to the minutest particulars, with the conditions found to exist in the region drained by the Columbia River.

The facts just enumerated concerning the Deccan trap have been taken from an admirable account of the geology of India, by Oldham.[1] A summary of the observations made on the trap sheets of India contained in this volume, might be transferred almost bodily to a description of the Columbia lava. On account of this double interest, I take the liberty of introducing it here:

"Recapitulating the whole evidence [concerning the Deccan trap], so far as it is presented to us by the observations hitherto made, we find that in times subsequent to the middle cretaceous, a great area of the Indian peninsula formed part of a land surface, very uneven and broken in parts, but to the eastward apparently chiefly composed of extensive plains, which, by some slight changes of level preceding the volcanic period, were converted into lakes. . . . The lakes had apparently been drained, and the deposits, which had accumulated in them, had locally been subject to denudation before the first outburst of lava took place. These occurred at considerable intervals, small and very shallow lakes or marshes being formed in the meantime by the interruptions to the drainage produced by lava flows, or by

[1] R. D. Oldham, "A Manual of the Geology of India," second edition. Calcutta, 1893, pp. 255–289.

changes of level accompanying the volcanic eruptions. In these lakes a rich fauna of fish, mollusca, entomostracous crustacea, and water plants existed, whilst a varied and probably a rich vegetation occupied the surrounding country. . . . Fresh flows of lava filled up the first lakes, and covered over the sedimentary deposits which had accumulated in the waters, but these very flows, by damming up other lines of drainage, produced fresh lakes, so that several alternations of lava and sedimentary beds were produced in places. Gradually the lakes seem to have disappeared, whether the lava flows succeeded each other so rapidly that there was no time for the accumulation of sediments in the interval, or whether, as is more probable, the surface had been converted into a uniform plain of basalt by the enormous lava streams which had been poured out, it is difficult to say, but no further traces of life have hitherto been found until towards the close of the volcanic epoch. It is possible that at the end, as at the commencement of the period, the intervals between eruptions became longer, and the animal and vegetable life, which may have been seriously diminished or altogether driven out of the country during the rule of igneous conditions, resumed its old position, but a great change had taken place in the long interval: the old lacustrine fauna had died out, and the animals and plants which now appeared in the country seem to have differed from those which had formerly occupied it. Lastly, in the northwestern portion of the area, parts of the volcanic country were depressed beneath the sea, and marine Tertiary deposits began to be formed from the detritus of the extinct volcanoes and their products. A great tract of the volcanic region, however, appears to have remained

almost undisturbed to the present day, affected by subaërial erosion alone, and never depressed beneath the sea level, though probably for a time at a lower elevation than at present."

A comparison of this account of the great basaltic sheets of India, with the description given later, of the similar area in America, will be found instructive.

Large portions of Abyssinia are reported to be covered by surface flows of lava, similar in many ways to those of India and America, but the evidence available concerning them is not sufficient to show conclusively that they are the result of what is understood as fissure eruptions.

In some regions, also, as for example the northwestern part of the British Islands and the adjacent region to the northwest, extending perhaps as far as Iceland, there are extensive systems of dikes, which at one time, there is little doubt, led to extensive surface flows. These eruptions were so ancient, however, and the region during its subsequent history so situated in reference to sea level, that erosion has removed all or nearly all of the surface layers, leaving only the truncated dikes that were formed by the filling of the fissures through which the extruded material found its way to the surface.[1]

Trap Rocks of the Newark System. — In the region occupied by the Newark system, on the Atlantic slope of North America and extending from Nova Scotia to South Carolina, there is one of the most extended series of dikes and sheets of igneous rocks thus far discovered. The length of this series from northeast to northwest is

[1] Archibald Geikie, "The Lava-fields of Northwestern Europe," in "Geological Sketches at Home and Abroad." New York, 1882, pp. 239–249.

about 1000 miles, and its width, although its eastern border is concealed by more recent deposits and by the sea, is not less than 200 miles. The area traversed by these dikes is nearly as great as that occupied by the Deccan trap or the Columbia lava; but unlike the regions where those formations were spread out, the Atlantic coast belt was an area of both sedimentation and deep erosion during and after the igneous invasion. The sheets of lava extruded at the surface became in part buried beneath subsequent sedimentary beds, and where erosion has been least, still survive. In the greater portion of the area along the Atlantic coast that was fractured so as to admit of the upward passage of molten rock from beneath, extensive and deep erosion has occurred, and only truncated dikes and remnants of igneous sheets remain. The dikes, in part, traverse rocks of Jura-Trias age, and their truncated summits, in certain localities, are buried beneath Cretaceous sediments.[1]

The several regions referred to above furnish indisputable evidence that fissures have been formed in the earth's crust, throughout great areas, during widely separated intervals of geological time, and that through these breaks vast quantities of molten rock have been outpoured. These, the greatest of all eruptions of volcanic material that have occurred since the dawn of what may be styled authentic geological history, have in most instances been accompanied by the formation of minor quantities of projectile material, such as lapilli, dust, etc. In the main, the deluges of molten rock occurred without the formation of craters or pronounced elevations of any

[1] I. C. Russell, "Correlation Papers — The Newark System." United States Geological Survey. Bulletin, No. 85, pp. 66–77.

kind. The layers occupy depressions and tend to subdue the inequalities in topography produced by previous upheavals and by erosion. The rocks poured out during fissure eruptions are dark, heavy, and, as will be explained in advance, are basic rocks, which fuse at a lower temperature than the more siliceous lavas, and when melted are highly fluid and flow rapidly, thus admitting of their expanding broadly into thin sheets.

Stages in the Lives of Volcanoes

Volcanoes, like many other features of the earth's surface, have their time of birth, periods of activity and decline, terminating at last in a time of repose, when they become silent and cold. These changes are less regular and less plainly the result of well-known laws than the similar sequence of events exhibited by other features of the land, and are apt to be considered, in part, at least, as of the nature of catastrophes. Could we take into account, however, all the forces that co-operate during the varying phases of the life history of a volcano, as, for example, the effects accompanying the cooling of the earth, the formation of thick layers of sediment charged with sea water, the manner in which surface waters find their way into subterranean regions, etc., it would probably be discovered that even volcanoes which break forth with severe earthquakes, and explode with such violence as to scatter rock fragments over half a continent, are in reality the result of slowly acting and finally culminating forces which obey definite laws.

However great the diversity that volcanoes display during their more active stages, there usually comes a

time in their decadence when they have marked similarities. As their energy declines they pass to a state of feeble activity, during which a moderate amount of heat is given off, accompanied by the escape of steam, carbonic acid, sulphuretted hydrogen, and other gases.

The earlier portion of this period of decline, when the rocks are still highly heated and at night appear red hot about the orifices from which steam issues with hissing and even a roaring noise, is termed the *fumarole stage*. Volcanoes in this condition emit sulphurous and hydrochloric acids and less quantities of sulphuretted hydrogen and carbonic acid gas. About the orifices when the rocks are sufficiently cool, deposits of sulphide of arsenic, chloride of iron, chloride of ammonium, boracic acid, and sulphur are frequently formed.

A more marked decline, known as the *solfatara stage*, is characterized by a marked decrease of heat and a less energetic escape of steam. The gases, in fact, as they pass off, are usually little if at all above the mean temperature of the atmosphere. The type of volcanoes in the solfatara stage is furnished by Solfatara, near Naples, from which the specific name is derived. From fissures in the floor of the crater of Solfatara there issue continually watery vapors, sulphurous acid, sulphuretted hydrogen, hydrochloric acid, and chloride of ammonium. The action of these substances upon one another, and upon the volcanic rocks through which they pass, gives rise to the formation of certain chemical products which, from a very early period, have been collected on account of their commercial value.[1] The rocks surrounding solfataras are frequently changed both in color and com-

[1] J. W. Judd, "Volcanoes." New York, 1881, pp. 213, 214.

position by the action of the gases that come in contact with them.

In the passage from the fumarole to the solfatara stage, the decrease in temperature is accompanied by a change in the nature of the gases emitted. Sulphurous and hydrochloric acids diminish, and the quantity of sulphuretted hydrogen and carbonic acid mingled with them proportionately increases.

When nearly all signs of volcanic activity have ceased, carbonic acid continues to pour forth, and being heavier than the air, tends to collect in low places, and forms so-called poison valleys, in which insects and even large animals sometimes perish. These manifestations of expiring energy are due mainly to contact of water with the hot rocks, and do not show that a conduit leading to subterranean reservoirs is still open. Fumaroles and solfataras are sometimes found during the early stages of volcanic activity, their energy increasing until explosions of steam or eruptions of lava occur; the eruptions being followed by long periods of decline, as already stated. The characteristics of the youth of volcanoes are thus repeated in what may be termed a second childhood.

A still later phase of volcanic energy, following the solfatara stage, and when gases no longer escape, is marked by the occurrence of hot springs and geysers. In regions covered with once molten rock, a great lapse of time is required for the heat to be conducted away. One of the processes by which this is accomplished, is by the percolation of rain water through the rocks, and its emergence at the surface as springs. Water passes underground for great distances, and also penetrates to a great depth, not usually in open passageways, but by perco-

lating through the interstices of the rocks themselves. The residual heat of volcanic beds is thus abstracted and conducted to the surface. Fissures intersecting the rocks aid the escape of the underground waters. Fissure springs thus formed are frequently of great volume, and pour forth with temperatures ranging from that normal to the rocks near the surface up to the boiling point of water, for the elevations where they occur.

Not all hot springs owe their temperatures to the residual heat of volcanic rocks, however, since water may penetrate to the subterranean regions that are affected by the general heat of the earth's interior and again reach the surface. The cooling of the earth is greatly assisted in this way. Motion along lines of fracture as where faults are formed, or rocks are folded and wrinkled, may also be transformed into heat by friction, and thus give origin to hot springs that are in no way different, so far as their surface manifestations are concerned, from those originating in other ways.

The three geyser regions of the world are in volcanic regions, but while geysers, on account of the source of the heat which is the mainspring of the striking phenomena they display, may be studied in connection with the subject before us, it seems best to defer their consideration and place them in the aqueous rather than the igneous branch of physiography.

Characteristics of the Products of Volcanoes

The matter emitted by volcanoes may for convenience be divided in general into two groups; namely, gases and solids. This is perhaps not a scientific classification, since during eruptions, much of the material included

among the solids is poured out in a liquid condition; and some of the gases and vapors are soon condensed into solids.

Gaseous and Sublimed Products. — Of all the gaseous or vaporous products discharged by volcanoes, steam is by far the most abundant, and may be considered as the mainspring, but not the ultimate cause, of many volcanic phenomena. No adequate measure of the amount of steam given off during eruptions, even of mild intensity, has been made, but that its volume is immense can readily be appreciated.

A visitor to Naples usually has his attention attracted by the "pine tree" of vapor that may almost always be seen in calm weather, towering above the summit of Vesuvius. Observers agree that this column is composed almost entirely of the vapor of water. During all stages in the activity of Vesuvius in recent centuries, this cloud has hung over the mountain, at times rising thousands of feet before expanding, and at other times, when the wind is strong, drifting away so as to resemble the cloud banners so frequently to be seen about Alpine summits. Day and night, and year after year, this great volume of steam has been pouring out of the crater, as if it was an immense boiling caldron — which in fact it is. When the activity increases, the steam issues under great pressure and with a roar that can be heard for many miles. The vapor column then becomes vastly enlarged and sometimes, on condensing, causes heavy rainfalls; thus demonstrating, on a grand scale, that it is the vapor of water which makes the mountain an object of dread.

It has been computed by Fouqué, that one of the numerous parasitic cones on the lava flows of Etna

emitted sufficient steam during one hundred days to form 462,000,000 gallons of water if condensed. All of the steam emitted by the numerous parasitic cones about that great volcano, however, if combined, would fall far short of the amount that escapes from its central crater.

The quantity of steam that escapes from volcanoes after they have passed to the condition of fumaroles and solfataras, is still immense. In numerous examples like Solfatara and Volcano, steam has been continuously emitted for centuries, with a roar like that produced when an ocean steamer reaches her moorings and the safety valves are opened.

Not only Vesuvius and Etna, but probably every other volcano that has been seen in action, emits steam which is derived from subterranean sources. From what is now taking place at hundreds of vents, it is safe to conclude that all the volcanoes that have existed on the earth throughout its geological history have been accompanied by the escape of steam from within the earth's crust.

Among the numerous questions which the observation of volcanoes had suggested, one of the most important is whether the steam they emit is derived from water present in the earth from the time it became a planet, or is the supply furnished by the descent of water from the surface? It is my intention to leave theoretical discussions until the student has made some advance in observation, but the analogy between volcanoes, geysers, and springs, as well as the study of volcanoes themselves, suggests an immediate answer to this query, to the effect that it is surface water which supplies the steam.

Of the gases and vapor emitted by volcanoes, it has been estimated that nine hundred and ninety-nine parts in

a thousand consist of steam. Of the substances given off in a gaseous condition with the steam, the most abundant is usually sulphurous acid. Chlorine is also present, and gives origin to hydrochloric acid; it is the pungent fumes of this acid which frequently makes a near approach to the crater of Vesuvius impracticable. Sulphuretted hydrogen is also emitted, and, being inflammable, sometimes burns with a bluish flame. With the exception of flames of burning hydrogen, noted below, this is nearly always about the only actual *burning* that accompanies volcanic eruptions, and is of decidedly minor importance as a part of the spectacle witnessed. The idea that a volcano is a "burning mountain" originated from seeing the glow of molten lava which is frequently reflected on the clouds of steam above a crater.

Hydrogen has also been found in volcanic gases. From observations made by Siemens, at Vesuvius in 1878, as stated by Geikie,[1] it was concluded that vast quantities of free hydrogen and of combustible compounds of that gas exist dissolved in the magma of the earth's interior, and that these rising and exploding in the funnels of volcanoes give rise to detonations and clouds of steam. When the source of the water which furnishes the steam of volcanoes is considered, it will be found that it is not necessary to consider that the free hydrogen given off by volcanoes is necessarily derived from the earth's interior, as just stated, as it may arise from the dissociation of descending surface water on coming in contact with ascending lavas. At the eruption of Santorin, in 1866, hydrogen was distinctly recognized by Fouqué, who for the first time established the existence of true volcanic

[1] Archibald Geikie, "Text-book of Geology," 2d edition, 1885, p. 183.

flames. These flames were again studied spectroscopically in the following year by Janssen, who found them to be due principally to the combustion of free hydrogen, but with traces of chlorine, soda, and copper. Fouqué determined by analysis, that immediately over the focus of eruption, free hydrogen formed thirty per cent of the gases emitted, but that the proposition rapidly diminished with distance from the active vents and hotter lavas, while at the same time the proportion of marsh gas and carbon dioxide rapidly increased.

The gaseous emanations collected by Fouqué were found to contain abundant free oxygen as well as hydrogen. One analysis gave the following: Carbon dioxide 0.22, oxygen 21.11, nitrogen 21.90, hydrogen 56.70, marsh gas 0.07=100.00. This mixture on coming in contact with a burning body at once ignites with a sharp explosion. These observations lead to the inference that the water vapor emitted from volcanic vents exists in a state of dissociation in the molten magma previous to its eruption. This conclusion is not only interesting in connection with volcanic studies, but highly suggestive in reference to our conceptions concerning the conditions existing within or below the earth's crust.

As already stated, a decrease in volcanic activity is usually accompanied by a change in the gases emitted. This is not only an increase in the percentage of the usually less abundant gases, owing to a decrease in the volume of steam poured out, but a variation in the nature of the gases with changing conditions. The nature of this change is believed to differ, however, in different volcanoes. In the case of Vesuvius, according to Sainte-Claire Deville, the most energetic eruptions are accompanied by the dis-

charge of chlorine, and to a less extent, by fluorine; while sulphurous gases are evolved during periods of lessening energy, being characteristic, in general, of solfataras, while carbonic acid becomes prominent in fumaroles.

Of the great variety of substances deposited on the cooler rocks in the vicinity of fumaroles and solfataras, the following may be enumerated, but the list is not complete. Sodium chloride (common salt) is sometimes abundant, and in the case of Etna is said to occur in such quantities as to be of commercial importance. The whitening of the country about Vesuvius by salt precipitated from the air during an eruption has already been noted. The common occurrences of salt in the vapors of volcanoes is one of the arguments sometimes advanced for the purpose of showing that eruptions are due to the access of sea-water to regions where rocks are highly heated. That salt may be derived from other sources, however, will be shown later. Ferric chloride is conspicuous about many volcanic vents, and coats the rocks with yellow and reddish incrustations that are frequently mistaken for sulphur. Sulphur also occurs, sometimes in large quantities, and in many localities is of commercial value. Ammonium chloride and boracic acid are among the products of solfataric action that are of economic importance. In addition to the more common substances just named, there are found sodium carbonate, sulphate of lime, specular iron, oxide of copper, and some rock-forming minerals.[1]

Liquid and Solid Products.—All rock material poured out of volcanoes in a highly heated and fluid or plastic

[1] For further information concerning the gases and vapors given out by volcanoes, consult J. W. Judd, "Volcanoes," pp. 40–44.

condition is termed lava, irrespective of its mineralogical or chemical composition. Much of the lava becomes cooled sufficiently, however, before its appearance at the surface, to be in a solid condition, but is still hot, and from its identity with the liquid lavas that have cooled on the surface is plainly of the same origin. The term *lava*, in fact, includes all of the solid and molten products of volcanic eruptions, except the fragments sometimes torn off by the volcanoes of the explosive type from the beds through which the extruded material passes in order to reach the surface. The fragments of limestone scattered over the sides of Vesuvius are examples of such non-volcanic intrusions in the midst of truly igneous material. Other similar examples will be cited later in connection with a description of the Mono craters, California.

The molten material which rises in the conduit of a volcano, but does not reach the surface, although it may be of the same mineralogical and chemical composition as that which is actually extruded, is not usually termed lava. Rocks formed in this way are called plutonic rocks. Between volcanic rocks or lavas and plutonic rocks, however, there is no well-defined boundary, although more or less marked physical and mineralogical differences result from the conditions under which they cool and harden. These differences will be noted on a subsequent page.

Lava Streams. — At times the column of molten rock in the throat or conduit of a volcano rises until the crater to which it leads is filled, and an overflow takes place across the lowest point in the crater's rim.

In some instances a stream of lava appears to form a channel for itself by melting the rocks over which it

flows, but that this is of common occurrence is doubtful. When the sides of a volcanic mountain are composed of light, incoherent scoria, lapilli, etc., such material may be carried away, some of it probably being fused. In this way a crater is sometimes breached, and a portion of its rim removed. Again, the pressure of the lava rising within a crater may be sufficient to rupture the walls that confine it. The bowl containing the molten rocks is thus broken and its contents escape.

A more common way in which craters discharge their lavas is by the opening of fissures in their sides. The lava is thus drawn off perhaps at the very base of a crater, leaving its rim unbroken. The immense pressure of a column of lava rising within a volcanic mountain greatly favors this mode of escape. In the case of the volcanoes on the Island of Hawaii, the lava sometimes issues from openings on the sides of the mountains and forms immense fiery fountains, several hundred feet in height, which play for days and even weeks. The immediate force which causes these great jets to rise is the static pressure of the molten rock at higher levels within the mountains.

The behavior of a lava stream after starting on its way down a mountain varies according to its degree of liquidity, the steepness of the slope, the character of the surface over which it flows, etc. At times the material is highly liquid and flows almost like water; again it is thick and viscid and descends slowly even on precipitous slopes. This difference in fluidity is due mainly to variations in the composition of the lava itself, some lavas fusing more readily than others, and also to the degree of heat that affects it. With sufficient heat all known substances

would become fluid, but the degree of heat that will cause certain lavas to become highly fluid will produce only a viscous condition in others.

Lavas may be divided into two somewhat well-defined classes, in reference to the amount of silica they contain; namely, basic and acid, as will be described more definitely in connection with the consideration of the classification of igneous rocks. The basic lavas are dark, heavy rocks rich in iron, and as a rule are much more easy of fusion than the usually lighter colored lavas, which are rich in silica. Marked mineralogical differences usually accompany the variations in silica, and, as stated by Dana, the fusibility is not controlled so much by the amount of silica, as by the nature of the minerals of which the rocks are composed, and especially by the variety of feldspar present. In basalt, the most easily fusible of volcanic rocks, the feldspar is mainly laboradorite, which fuses easily. Augite is also present, which is rich in iron, and is likewise of comparatively easy fusibility. When basalt is melted but not thoroughly fused, the more refractory minerals it contains float in the magma formed by the fusing of the feldspar and augite.

As the nature of the material put in a blast furnace determines the readiness with which the charge may be melted, so, in nature, the composition of the fused rocks in volcanoes determines the readiness with which the lava discharged will flow.

As already stated, the degree of heat to which a volcanic magma is exposed also influences its liquidity; the presence or absence of water is again an important condition, since aqueo-igneous fusion is effected at a much lower temperature than what may be termed dry fusion. The

study of the condition in which lava reaches the surface seems to show, however, that it is variation in the composition of lavas and in the amount of water contained in them, rather than variation in temperature, which control the marked contrasts observed in their fluidity.

It has been stated from what may be termed casual observations, that the lava flowing through tunnels on the Island of Hawaii sometimes rushes along at the rate of forty miles an hour. No measurements to sustain this statement, however, have been made. A great surface flow of lava on Hawaii, in 1852, advanced twenty miles in as many days. Another stream, emitted in 1859, advanced thirty-three miles in eight days, corresponding to an average rate of four miles a day on a mean slope of one foot in fifteen. A stream about thirty miles long, in 1880 and 1881, advanced for nine months, on a mean slope of one foot in thirteen, or about five degrees.[1]

It needs no argument to show that the rapidity with which lava streams flow will depend largely on the slopes of the surfaces they descend, since they must obey the laws of dynamics as applied to liquids. Other conditions being the same, the steeper the slope the more rapid will be the flow.

The topography of a region over which lava flows also influences the shape of the stream and the rate at which it will advance. For example, if the sides of a volcano are channelled by descending valleys, the lava gathering in such depressions will be confined, thus diminishing radiation and admitting of a quicker and greater advance than if it should spread out on a uniform, uneroded slope.

[1] J. D. Dana, "Characteristics of Volcanoes," New York, 1890, pp. 238, 239.

The lava streams of the Hawaiian islands are composed of basic lava, and, as already stated, are highly fluid at the time of their extension. Where the descent is somewhat precipitous, they flow rapidly, and at first are almost as liquid as water, but on reaching the base of the mountain they expand laterally and flow more slowly, owing in part to a decrease of fluidity due to loss of heat. The length of these streams is sometimes between forty and fifty miles.

Acid lavas, on the other hand, are usually thick and viscous, and flow sluggishly even on steep mountain sides. Frequently a stream of acid lava will cool and harden on a slope down which a basic flow would plunge in a cataract of fire. The tendency of basic lavas is to spread out in thin sheets, which terminate with low frontal slopes, although a thin margin is by no means the universal rule; while the tendency of acid flows is to form thick sheets with precipitous, and in some cases, almost overhanging cliff-like margins.

Tunnels in Lava. — The conditions controlling the rate of flow of lava streams also influence various phenomena displayed by them as they advance and gradually cool. In the case of highly liquid lavas especially, the surface hardens, while the still molten portion beneath flows on. When the flow is rapid, this crust is usually broken before it can reach sufficient thickness to support its own weight, and the cakes of hardened rock either sink and are remelted, or are swept along in confused piles. When the advance is slow, or is checked and starts again when the liquid portion below finds an escape, the hardened surface is left as a roof over the space vacated by the draining away of the molten rock beneath. Caverns of

this nature are of common occurrence in lava-covered regions, and may sometimes be followed for a mile, or perhaps several miles, although they are frequently obstructed by the falling in of portions of their roofs. Examples of caverns formed in the way just described will be noticed in giving an account of the volcanoes of Utah and California.

The descent of heated waters into lava caverns sometimes leads to the formation of curious stalactites, which differ, however, from those of limestone caverns. A study of these peculiar forms has been made by Dana[1] and others.

The Aa Surfaces of Lava Streams. — The hardening or freezing over of lava streams while the magma beneath is still flowing, leads, as already stated, to the fracturing of the crust and the displacement of the blocks thus formed. Under the proper conditions affecting the rate of cooling and the flow of the still plastic interior of a stream, the surface blocks are carried along, and when the lava finally hardens, are left in a state of utmost confusion. Sometimes the blocks are piled in huge heaps, and again the general surface, although nearly horizontal, is composed of cakes of lava inclined in all directions, and is all but impassable.

In the Hawaiian islands surfaces of this description occur over areas many square miles in extent, and are known by the native name *Aa.* This name has been adopted into the technical language of geology, and found to be useful in describing many volcanic regions.

[1] E. S. Dana, "Lava Stalactites from Caverns in Mount Loa Lava Streams," in "Characteristics of Volcanoes," by J. D. Dana, 1890, pp. 332-342.

Characteristic aa surfaces occur on every variety of lava, but are most pronounced, perhaps, on those of the acid type. When the flowing magma is but imperfectly fluid, a slight loss of heat leads to the hardening of the surface, and the conditions favoring to the formation of aa are soon reached. The surface sheet of fragments is then thick, and, indeed, in some instances the entire stream becomes charged with angular rock masses, held in a still viscid magma. Such a stream on solidifying forms one variety of what is termed a volcanic breccia.[1]

The fact that the blocks of lava seen on aa surfaces actually floated on the viscid stream of molten rock flowing beneath them is sometimes shown by grooves and striations on their under surfaces. As the blocks are carried along they grind against each other, making a harsh noise. In this respect partially congealed lava streams form a marked contrast to the advance of more liquid lavas, which under similar topographic conditions flow quietly.

The formation of aa on Hawaii is thus described by Dutton:[2] "Upon the mountain slopes the lava runs with great velocity, and the streams are correspondingly narrow. But when it strikes the nearly horizontal plain below, its velocity is checked, and the liquid accumulates in great volume, becoming viscous by cooling. Its flow is greatly retarded, and yet the mass is sufficient to en-

[1] A breccia is a rock composed of or containing angular fragments. A sedimentary breccia consists of angular fragments of older rocks of any character cemented together by mud, sand, etc. In cave breccia, angular fragments are united by the deposition of calcium carbonate, etc.

[2] C. E. Dutton, "Hawaiian Volcanoes," U. S. Geological Survey, 4th Annual Report, 1882–83, p. 157.

able it to move with a slow motion analogous to that of a glacier. When the viscosity of the lava becomes very great, it is in a condition which enables it to yield to strains of a certain amount; but if that strain is exceeded, it is crushed and ground up. The movement which takes place at this stage is partially a plastic yielding, more particularly of the interior and hotter parts, and partly a shattering and grinding up of the outer, stiffer, and colder parts. This glacier-like motion, however, is possible only with very large masses of the lava, which still retains a sufficient quantity of heat to maintain a plastic condition. Persons who have witnessed the movement of a clinker field in the last stages of an eruption describe it as being so slow as to be quite imperceptible until it has been watched for a long time, and as being attended with a crunching noise which comes in volleys like the report of musketry."

The aa surfaces of lava streams resemble in some respects the surfaces of northern ice flows, where blocks of ice are ground together and forced far up shelving shores by the pressure of the wind and of water currents.

Although the surfaces of basaltic lavas are frequently rough, on account of the method of cooling described above, their ruggedness is mild in comparison with the surfaces of some acid lavas, as rhyolitic obsidian, for example, which is in reality a glass, and breaks with sharp points and blade-like edges. An example of this nature is furnished by the streams of obsidian on the sides of the Mono crater, California. An attempt to cross such a field of jagged and angular fragments of glass is perilous to life and limbs.

The Pahoehoe Surfaces of Lava Streams. — While the surfaces of thick sheets of basalt are broken and rendered rough and uneven in the manner already described, thin sheets cool rapidly without breaking into cakes, but frequently become wrinkled, owing to the sluggish flow of the thickening magma. At times these wrinkled and ropy surfaces are smooth, resembling somewhat in appearance the surface of wind-rippled mud, and again they are scoriaceous and rough. These variations depend on the nature of the lava and the conditions under which it cools. These wrinkled surfaces frequently form swelling or oval masses, which overlap and merge with another.

To this peculiar and characteristic variety of lava surface, the natives of the Hawaiian islands have given the name *Pahoehoe*. Its appearance is thus described by Dutton, in the report just cited: [1]

"Imagine an army of giants bringing to a common dumping-ground enormous caldrons of pitch and turning them upside down, allowing the pitch to run out, some running together, some being poured over preceding discharges, and the whole being finally left to solidify. The individuality of each vesselful of pitch might be half preserved, half obliterated. The surface of the entire accumulation would be embossed and rolling, by reason of the multiplicity of the component masses, but each mass by itself would be slightly wrinkled, yet, on the whole, smooth, involving no further impediment to progress over it than going up and down the smooth-surfaced hummocks."

As the surface and outer margin of a stream of lava

[1] Page 95.

becomes clogged with fragments resulting from its cooling and breaking, it advances slowly, but owing to ruptures in the thickened and hardened surface, the still liquid interior escapes from its margin from time to time, being forced out by the pressure from within. The material thus extruded by reason of its high temperature and fluid condition flows rapidly, spreads out in thin sheets, but cools quickly. Again taking the evidence of an eyewitness: "Scarcely is one of these little offshoots of lava cooled when it is overflowed by another and similar one, and this process is repeated over and over again. In a word, pahoehoe is formed by small offshoots of very hot and highly liquid lava from the main stream, driven out laterally or in advance of it in a succession of small belches. These spread out very thin, cool quickly, and attain a stable form before they are covered by succeeding belches of the same sort."

The Scoriaceous Surfaces of Lava Streams. — A characteristic of molten lava is that it contains steam and other vapors or gases occluded in its mass. The rock is in a state of aqueous-igneous fusing; that is, the presence of water allows it to become liquid at temperatures which in the absence of water would not induce a change to a fluid condition. Occluded steam expands when the lava rises toward the surface and pressure is relieved, and much of it escapes, as is shown by the clouds that form over lava flows. The rapidity with which the occluded steam expands depends not only on the temperature and the rate at which pressure is relieved, but also on the character and condition of the lava. When the lava is highly fluid so as to resemble the liquidity of water, the steam escapes readily; when it is more viscous, the steam is retained,

but expands so as to make the rock open and scoriaceous in structure. Acid lavas, being especially favorable for the retention of the steam, are frequently expanded into a light, frothy substance, termed *pumice.* Owing to movements in lava after steam cavities are formed in it, the vesicles are frequently drawn out so as to become elliptical or even greatly elongated. The more basic rocks, as basalt, are also affected in the same manner, and become scoriaceous or full of steam cavities, although the process is seldom carried far enough to produce pumice.

The formation of steam cavities in still plastic lava may be illustrated by what takes place in bread-making. The carbonic acid generated in dough expands and gives the plastic mass an open, cellular structure; when the dough is hardened by baking, the cavities remain, separated one from another by thin partitions. The carbonic acid in the dough plays the rôle of the steam in still plastic lava, although the expansion of the steam is due to relief of pressure. The lava which has been thus affected, when cooled and hardened, has an open, cellular structure similar to that of bread. A lava filled with an abundance of steam cavities is said to be *scoriaceous.*[1] Variations in scoriaceous rocks occur, depending largely

[1] Igneous rocks containing steam blebs, on cooling and even long after they have lost all of their heat, become permeated with water which percolates through them and dissolves some of their mineral constituents. The material thus dissolved is in many instances redeposited in the cavities, which thus become filled with various minerals. Of the minerals thus deposited, quartz is the most common. When the steam cavities are filled in this manner, and the rock is broken open, hard kernels resembling almonds in shape are found in the openings. Such rocks are called *amygdaloids.* It is to be remembered that in such instances the amygdules are of secondary origin. Agates are formed by this process of infiltration. Geodes are similar cavities not completely filled.

on the size of the cavities and on the thickness of the walls between them. The cavities are of various diameters, from a small fraction of an inch up to an inch or two.

When the pressure to which the steam in lava is subjected is sufficient, it is prevented from expanding. As the steam escapes, the cavities are closed on account of the pressure about them. It thus happens that lava streams become scoriaceous on their upper surfaces, while within they cool into compact, stony masses, without cavities visible to the eye. A characteristic feature of thick lava flows is, for this reason, the presence of a scoriaceous and porous surface layer, which grades into compact rock below.

When the lava is of the proper consistency, steam rises from several inches, and perhaps several feet, below the surface, and tortuous tubes are formed. Again, the passageways for the escaping steam may unite as they approach the surface and lead to the blowing out of more or less material, and the formation of parasitic cones, which have many of the characteristics of true volcanoes. In fact, these parasitic cones are volcanoes in miniature, and differ from primary volcanoes mainly in the fact that the supply of steam and molten rock is small in amount. Parasitic cones are sometimes common on lava flows, and may reach a height of even a few hundred feet and have craters at their summits. They are commonly formed of fragments of scoriaceous lava, and emit steam with explosive violence, but seldom give origin to streams of molten rock.

The upper surfaces of lava streams, then, are characterized by various features, resulting from the manner in

which the lava cools; rough aa surfaces occur under certain conditions, smooth but wrinkled and mammillary surfaces under other conditions; local concentration of the escaping steam leads to the formation of parasitic cones, and in most cases the surface portions are open and cellular.

When a sheet of lava is poured out over the surface of a previous one, the plane of separation is sometimes marked by the characteristics just enumerated, but in some instances of this nature the scoriaceous surface of the older sheet seems to have been fused by the heat of the superior layer, so that the two flows are cemented together and the plane of separation is indefinite.

In the walls of the canyons cut through the Columbia lava in Washington, Oregon, etc., ten or more separate flows may be distinguished, which appear almost as evenly stratified as layers of sedimentary rock. In these instances, however, the adjacent layers of basalt are sometimes separated by sheets of fragmental volcanic material, produced by violent explosions, and by lacustral sediments, as well as by scoriaceous surfaces.

Characteristics of the Bottoms of Lava Flows. — As a lava stream advances, especially during the later stages of its flow, when the surface and margins are in the condition of aa, the blocks cooled at the extremity may be carried under the advancing mass and thus transferred to the bottom of the sheet. Outflow of liquid lava cooling quickly into pahoehoe may become buried in a similar manner. Scoriaceous lava may thus occur on the under side of a lava sheet, as well as on its upper surface.

Loose masses of rock lying in the path of an advancing lava stream may become involved in its lower portion,

and cracks and openings of various forms, in the floor over which lava flows, may become filled. When lava advances over mud or other loose deposits, they may become involved in the fused rock and perhaps melted or greatly changed.

The rocks over which lava spreads are usually altered in color and texture as a result of heating, and frequently have minerals deposited in them by the heated waters that percolate through them. Changes of this nature are embraced in what is termed *contact metamorphism*. The extent of such metamorphism varies, being only a few inches in some instances, and again, when the thickness of the cover of volcanic rock is no greater, reaching many feet and perhaps several yards. The principal condition controlling the extent to which sedimentary beds are altered on account of the flow of lavas over them, seems to depend on the amount of water they contain. Dry heat induces only local changes; heat accompanied by moisture brings about much deeper alterations.

When lava flows over a land surface, the soil is baked and usually reddened by the heat; if ponds of water are encountered, steam explosions result, and may lead to the formation of parasitic cones on the surface of the flow, and to the formation of sheets of volcanic fragments. Instances are on record in the case of Etna, where lava flowed over cisterns filled with water, the steam escaping through the lava caused the blowing out of scoria and lapilli and the formation of miniature cones of eruption.

Lava streams sometimes advance into the sea, and may be formed on the sea bottom from submarine volcanoes. The characteristics of the surfaces of such flows which would enable one to distinguish them from subaërial

lavas, have not been clearly determined. The study of ancient lava sheets seems to indicate that less striking differences occur between subaërial and subaqueous extrusion, than at first might be surmised.

The Crystalline Structure of the Central Portions of Lava Sheets. — As is well known, if fused slag, or glass, is cooled quickly, crystals are not developed, but the mass when solid has a glassy or stony structure. When such material is cooled slowly, however, crystals of various minerals are formed in a glassy ground mass, the crystals being larger and more perfect the slower the rate of cooling. The same principle holds good in the cooling of lava. When the lava is in thick sheets, the central portions cool much more slowly than the top and bottom, and acquire a coarsely crystalline texture, while the more quickly cooling portions above and below are frequently without crystals that are visible to the eye, and may appear glass-like or amorphous in texture, even when examined in thin sections under the microscope.

When rock cools from a state of fusion, division planes or *joints* are frequently developed, which divide the hardened rock into prisms. It is then said to have a *columnar structure.* The central portions of lava sheets, owing to the slowness with which they cool, frequently become beautifully columnar; while the more rapidly cooling basal and surface portions are either not jointed or are broken in a confused and irregular manner in many directions. The prisms or columns formed during the slow cooling of lava are many times very regular, and always have their longer axes at right angles to the cooling surfaces. When a lava sheet is cut through by stream erosion or broken so that a section is exposed, it fre-

quently presents the appearance of a long colonnade, the columns merging above and below into portions of the sheet which are not conspicuously jointed. In some instances the central, columnar portion is from fifty to a hundred or more feet thick, while the individual columns, in most instances broken by cross-joints, are from a few inches to eight or ten feet in diameter. Usually the columns are six-sided. Variations in all of the dimensions mentioned, however, are of common occurrence.

It frequently happens that steam holes in lava sheets, extending from a considerable depth to the surface, lead to irregularities in the cooling surfaces, and the resulting columns, instead of being vertical and regularly formed, are grouped about the centre from which the heat escapes, and radiate in all directions. Not infrequently, too, they are curved instead of straight, and show other irregularities.

The marked variations in different portions of lava sheets are of interest especially in aiding one to interpret the appearances presented by ancient rocks of similar origin, and in determining the character of former eruptions. These, and other features also, enable one to distinguish surface flow, or *extruded* sheets, from layers of molten rock forced in among stratified beds, and termed *intruded* sheets. The characteristics of intruded sheets will be noted in describing the origin and nature of subterranean igneous rocks.

The Fragmental Products. — During volcanic eruptions, except of the most quiet character, fragments of rock are blown into the air and distributed more or less widely over the surrounding region. The material thus blown

out may be divided into two groups: the first, including such portions as are plastic when they fall, and the second, such lava fragments as have been torn off of the sides of the craters by the violence of the outrushing steam, and also the liquid lava which is blown into the air, but cools and hardens before reaching the earth. This grouping is arbitrary, as there is no sharp division between plastic and solid volcanic projectiles, but is convenient for purposes of description and study.

An example of the manner in which liquid lava is thrown into the air, is furnished by the lava fountains that play on the surface of the lake of molten rock in the crater of Kilauea. As described by many observers, columns of lava, almost as liquid as water, are there shot upwards to a height of several hundred, and in some instances of nearly a thousand, feet. The projecting force in these and all other similar instances is mainly, and probably wholly, steam. The molten rock falls before cooling. The most of it returns to the boiling lake of lava from which it rose, but some of the drops and clot-like masses reach the floor of the crater beyond the limit of the lake, and on hardening form scoriaceous masses which add to the accumulations of solid material.

Driblet Cones. — When the fountain-like eruptions of molten rock in Kilauea are less energetic, and especially when they rise through fissures in the crust that floors the crater, the lava divides into drops and falls about the orifices. The drops, being yet hot and plastic, adhere one to another and build chimney-like piles, which Dana has termed *driblet cones*. These are formed of scoriaceous, clot-like masses which are sometimes nearly spherical. These semi-fused masses are piled one on another

in such abundance as to form steep conical piles, in some instances a hundred feet or more in height. Occasionally the particles of projected lava are small and descend in showers of loose, smooth-faced, but variously shaped bullets and granules about the vents.[1]

The conditions most favorable for the building of driblet cones occur when the lava is highly fluid, is projected into the air through small openings, and cools sufficiently to become solid but yet plastic before falling. So far as has been reported, these conditions are found only in basaltic craters. The usually thick and pasty consistency of acid lavas does not favor the growth of such piles of congealed projectiles as occur in the crater of Kilauea.

Pele's Hair. — The air above the seething lake of molten lava on Kilauea is sometimes filled with gossamer threads of glass, which are carried away by the wind and accumulate in large quantities on the adjacent cliffs. This substance is known as Pele's hair, in memory of the Hawaiian goddess of the volcanoes. It furnishes a convenient and suitable material, with which birds build their nests.

The capillary threads of glass forming Pele's hair resembles the "mineral wool" used as an insulating material for steam pipes, etc., which is obtained by conducting a stream of molten slag in front of a strong steam jet; the slag is blown away by the force of the steam, and separates into drops which are drawn out into hair-like threads.

When individual threads of Pele's hair are examined

[1] J. D. Dana, "Characteristics of Volcanoes," New York, 1890, pp. 158–160.

under the microscope, they are not found to be even and regular. The threads are often tubular, and sometimes branch, or two threads are welded where they cross each other. The glass composing the threads and tubes is far from being pure, but contains rhombic crystals of various minerals as well as air cavities, about which there are expansions of the enclosing glass. The crystals were evidently floating in the molten magma before it was spun out.[1]

The commonly accepted explanation of the formation of Pele's hair, is, that drops of fluid lava are thrown into the air during the jetting and splashing of the boiling lava, and drawn out into hair-like threads by the action of the wind. Dutton states, however, that nothing of this sort was to be observed during his visit to Kilauea, and yet Pele's hair was forming in great abundance. Wherever the surface of the molten lava was exposed by the breaking up and sinking of the hardened crusts formed on it, the air above was filled with filaments of glass, even when there was no spurting or apparent boiling of the molten material. The explanation of the phenomena offered by Dutton is as follows: [2]

"Liquid lava coming up from the depths always contains more or less water, which is given off slowly and by degrees, in much the same way as champagne gives off carbonic acid when the bottle is uncorked. Water vapor is held in the liquid lava by some affinity similar to chemical affinity, and though it escapes ultimately, yet

[1] Descriptions and figures of Pele's hair are given by J. D. Dana, "Characteristics of Volcanoes," pp. 160–161, who cites the microscopical studies of C. Fr. W. Krukenberg.

[2] C. E. Dutton, "Hawaiian Volcanoes," U. S. Geological Survey, 4th Annual Report, 1882–83, p. 108.

it is surrendered by the lava with reluctance so long as the lava remains fluid. But when the lava solidifies, the water is expelled much more energetically, and the water vapor separates in the form of minute vesicles. Since the congelation of all siliceous compounds is a passage from a liquid condition through an intermediate stage of viscosity to final solidity, the walls of these vesicles are capable of being drawn out as in the case of glass. The commotion set up by the descending crusts produces eddies and numberless currents in the surface of the lava. These vesicles are drawn out on the surface of the currents with exceeding tenuity, producing myriads of minute filaments, and the air, agitated by the intense heat at the surface of the pool, readily lifts them and wafts them away. It forms almost wholly at the time of the break-up. The air is then full of it. Yet I saw no spouting or sputtering, but only the eddying of the lava like water in the wake of a ship. The country to the leeward of Kilauea shows an abundance of Pele's hair, and it may be gathered by the barrelful. A bunch of it is much like finely shredded asbestos."

Volcanic Bombs. — During explosive volcanic eruptions masses of plastic lava are sometimes hurled high in the air, and on account principally of their irregularities of form, acquire a rotary motion, which tends to make them spherical. These revolving masses commonly cool sufficiently to harden before reaching the earth, and are more or less perfectly spherical, but at times are still sufficiently plastic when they strike, to be flattened into oval cakes. Projectiles of this nature are termed *volcanic bombs.*

The fact that volcanic bombs rotate during their flight through the air is shown not only by their characteristic

ball-like forms, but also by spiral ridges which sometimes converge towards opposite poles, thus showing the position of the axis on which they revolved. Their internal structure sometimes furnishes evidence sustaining the same conclusion. In an example figured by Darwin,[1] there is a well-defined shell of compact lava near the exterior, having a nearly uniform thickness of about the third of an inch; within is a scoriaceous mass, in which the cells are largest at the centre of the bomb and decrease in size to the inner surface of the enclosing shell. Darwin's explanation is that the exterior cooled rapidly, and did not allow the steam it contained to expand, while the still plastic central portion cooled slowly. Owing to the centrifugal force due to rotation, pressure was relieved at the centre and allowed the core of slowly cooling lava to become cellular.

The distance from a volcano at which bombs may fall must evidently depend not only on their initial velocity, but on the angle at which they start on their flight. During an eruption of Cotopaxi, bombs were thrown a distance of nine miles.

Lava balls are described by Dana[2] as occurring on Hawaii, that resemble bombs in appearance, but owe their form to a rolling motion in the forward portion of an advancing aa stream, due to friction on the bottom. Certain so-called bombs on Vesuvius are thought to have a similiar origin.

Scoria Cones. — Lava not sufficiently fluid to fall in

[1] Charles Darwin, "Geological Observations on Volcanic Islands," 1844, pp. 36, 37.

[2] J. D. Dana, "Characteristics of Volcanoes," pp. 11, 245. A reference is given by Dana to "The Fragmentary Ejectamenta of Volcanoes," by Johnson-Lewis, in "Am. Jour. Sci.," 1888, Vol. 34, p. 103.

drops as in the formation of driblet cones, and not projected with sufficient velocity to give origin to bombs, frequently falls about a volcanic vent in thick, clot-like masses which are still plastic when they reach the earth, but more frequently, perhaps, cool and harden into rough, scoriaceous, slag-like masses before coming to rest. These masses, of various size up to perhaps a foot or two in diameter in many instances, accumulate about the orifice from which they were projected and build up conical piles with depressions in their summits. The "cone of eruption" usually to be seen within the crater of Vesuvius is of this nature. Such cones are common in most volcanic districts, and may attain vast dimensions. Scoria cones grade into others formed of smaller projectiles, averaging about half an inch in diameter, and termed *lapilli*, the term having been adopted from the Italian name for the small, gravel-like accumulation of scoriaceous fragments about Vesuvius. Scoria and lapilli are of like origin, and commonly occur together in the same cones; when the former predominates, a scoria or "cinder" cone results, and when the latter is in the greater abundance, lapilli cones are formed.

Still finer projectiles of the same character as lapilli pass under the names volcanic gravel, volcanic sand, and volcanic dust, according to size. The finest volcanic ejectamenta are sometimes termed *volcanic ashes*, but as this term conveys the idea that they are the residue left by combustion, it is a misnomer and should not be used.

Sheets of Volcanic Sand and Dust. — In the case of volcanic eruptions of the explosive type, the steam occluded in the lava expands as external pressure is relieved; this

expansion is frequently so violent that the rock is disintegrated and the fragments projected high in the air. Beside this primary mode of reducing the lava to fragments, and much of it to the condition of dust, the larger fragments as they are shot upwards with a velocity in some instances even greater than the initial velocity of shells fired from modern rifle-cannon, strike against one another and against falling fragments, and are shattered, thus tending to increase the quantity of fine, dust-like particles produced. While much fine material originates thus, and is carried away by the wind, many of the fragments that escape comminution fall into the crater from which they were thrown and are again violently ejected, thus multiplying the chances of their being reduced to powder. An eruption of the explosive type thus tends to form much fine dust, which is carried high into the air by the upward rushing steam and falls most abundantly near the place of discharge. Should a strong wind be blowing, the dust is carried to leeward of the volcano, and on reaching the earth forms a sheet, which, owing to the winnowing action of the wind, is composed of finer and finer fragments, the greater the distance from the volcano.

The wide distribution of the dust of Krakatoa, which was probably deposited over the entire earth's surface, has already been referred to. Many instances are on record of volcanic dust falling hundreds of miles from the parent volcano. It is not an unusual occurrence for vessels far out at sea to encounter showers of volcanic dust, which whiten their decks. During the winter of 1875–76 dust fell in Norway which was similar to that previously erupted from volcanoes in Iceland, and it was predicted that some volcano on that distant island was in a state

of eruption; intelligence received several weeks later confirmed the correctness of this conjecture.[1]

The steam clouds so frequently seen rising from volcanoes in a state of mild activity when illuminated by the sun are of a brilliant, fleecy white; should the steam explosions become more violent, the color of the column is frequently changed to an inky blackness. This is due to the vast quantities of dust and stones shot upward with the steam. A graphic account of the projection of a dark cloud of volcanic dust from Cotopaxi on July 3, 1880, is given by Whymper,[2] in recording his observations while on the summit of Chimborazo:

"The sky was bright, the air serene; and long before dawn, sixty miles away, we saw the cone of Cotopaxi clear cut against a cloudless horizon, and remarked how tranquil the great volcano looked, and that not a sign of smoke was rising from the crater. . . . At 5.40 A.M. two puffs of steam were emitted, and then there was a pause. At 5.45 a volume of inky blackness began to rise, and went up straight in the air with such prodigious velocity that in less than a minute it had risen 20,000 feet above the rim of the crater. I could see the upper 10,000 feet of the volcano, and estimated the height of the column at double the height of the visible portion of the mountain. The top of the column, therefore, was nearly 40,000 feet above the level of the sea. At that elevation it encountered a powerful wind blowing from the east, and was rapidly borne towards the Pacific, remaining intensely black, seeming to spread very slightly,

[1] J. W. Judd, "Volcanoes," p. 72.

[2] Edward Whymper, "Travels amongst the Great Andes of the Equator," New York, 1892, pp. 320–330.

and presenting the appearance of a gigantic ¬, drawn upon an otherwise perfectly clear sky. It was then caught by wind from the north, and, borne towards us, appeared to spread quickly. . . . For a full hour we saw the immense column still rising from the crater, and then the clouds which were drifting towards us shut it out.

"When they commenced to intervene between the sun and ourselves, the effects which were produced were very truly amazing. We saw a green sun, and smears of color something like verdigris-green high up in the sky, which changed to equally extreme blood-red, or to warm brick-red, and then passed in an instant to the color of tarnished copper, or shining brass. No words can convey the faintest idea of the impressive appearance of these strange colors in the sky, — seen one moment and gone the next, — resembling nothing to which they can properly be compared, and surpassing in vivid intensity the wildest effects of the most gorgeous sunsets.

"About midday the cloud passed overhead, having taken six hours to travel about eighty miles. The sun then became invisible, and the temperature fell to 15° F.

"When the clouds from Cotopaxi first passed overhead, they were still, I think, not less than 5000 feet above us (or 25,000 to 26,000 feet above the sea), and they extended far to the south before the dust of which they were composed began to fall upon the summit of Chimborazo. It commenced to settle about ten minutes after our arrival, and in the course of an hour caused the snowy summit to look like a ploughed field. It filled our eyes and nostrils, rendering eating and drinking impossible, and at last reduced us to breathing through handkerchiefs."

This discharge of dust, as ascertained later by Whym-

per, fell over many hundreds of square miles. Its amount was estimated at not less than two millions of tons; equal to a column of solid lava (2.65 specific gravity) 38 feet square and 18,600 feet high.

The dust which fell on the summit of Chimborazo was examined microscopically by Professor Bonney, and found to consist of mineral and glass fragments from .02 inch in diameter downwards.

The instructive eruption from Cotopaxi witnessed by Whymper, although small in comparison with many discharges of dust that have occurred, enables one to obtain a graphic idea of what takes place when sheets of fine fragments like those which occur in the far west, not only hundreds but thousands of square miles in area and with an average depth of twenty feet or more, are deposited over the land. The sheets of volcanic dust referred to will be described later in connection with other volcanic phenomena in North America.

An interesting variation in the manner in which steam escapes from a volcano has been noted in the case of the volcano known as Akutan, on an island of the same name, Alaska. In calm weather immense rings or wreaths of black, dust-charged steam rise from the summit of the mountain and float away one after another and gradually expand as they rise. These wreaths appear to be vortex rings similar to those sometimes blown out of the smoke-stack of a locomotive. Akutan has not been closely examined, but apparently it has a deep funnel-shaped crater, and the steam escaping from the liquid lava deep within its throat blows out dust-charged steam in the manner in which vortex rings are found in laboratory experiments. When the volcanic wreaths are less

well defined, the ascending steam column, corresponding with the pine tree of Vesuvius, has what appears to be a spirally twisted trunk.

Profiles of Volcanic Mountains

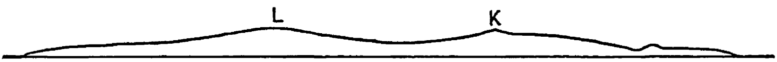
The two varieties of volcanic eruptions, the quiet and the explosive, characterized respectively by the emission of streams of highly liquid lava, and the blowing out of fragments, lead to the building of two well-marked types of mountains.

When lava is poured out in a highly liquid condition, it flows rapidly, frequently reaching a distance of fifty miles or more, and under favorable topographic conditions spreads out widely so as to form thin sheets. A succession of flows of this nature from the same vent leads to the piling up of layer above layer until a mountain with a broad base and gentle slopes is formed. Of such mountains Mauna Loa may be taken as the type. Its base at sea level is between fifty and sixty miles in diameter. The mean slope within a circle of five miles about the summit crater, as stated by Dana, is about three degrees. At a greater distance from the crater the slope increases to an average of perhaps five degrees. The mountain is thus a flat-topped dome. The reason for the increase in slope at a distance in excess on an average of five miles from the crater, is that the outbursts of lava are usually from the sides instead of the summit of the mountain.

Volcanoes in a state of explosive eruption, as we have seen, project scoria, bombs, lapilli, dust, etc., high in the air. Much of this material falls about the orifice from which it was thrown and builds up a cinder, or lapilli

cone: the larger fragments as a rule fall near the place of eruption, while smaller ones may be carried a great distance. When the eruptions are long continued, conical mountains are formed by this process, the sides of which are steep. In many instances, their outer slopes have an inclination of thirty to forty degrees. The angle is determined by the "angle of repose" of the material of which the cones are built, and varies with the size and angularity of the fragments. Mountains of this type are illustrated especially by Fusiyama, Japan (Plate 3);

PROFILE OF SHISHALDIN; DRAWN FROM A PHOTOGRAPH; SCALE ABOUT 10,000 FT.= 1 INCH.



PROFILE OF LOA AND KILAUEA; AFTER J. D. DANA; SCALE ABOUT 10 MILES = 1 INCH.

Fig. 2. Profiles of volcanic mountains. The upper diagram shows the characteristic outline of a cone resulting from mild explosions; the lower diagram, the form produced by the quiet effusion of highly liquid lava.

Shishaldin, on Unimak Island; and St. Augustine, Cook's Inlet (Plate 3), Alaska. Nearly all of the conical volcanic piles on the earth are of this class, but in most instances the regularity of their slopes has been modified by overflows, or outbreaks of lava, and by erosion.

Not only are the sides of volcanic cones built of fragmental material, steep, as already mentioned, but when seen in profile they present regular and very beautiful curves, as may be seen from the accompanying illustration of Fusiyama. The reason for this characteristic curva-

ture, as determined by Becker,[1] is that it is the figure of greatest stability.

Between dome-shaped volcanic mountains with flat tops, and conical piles with a sharp apex and concave surfaces, there are many intermediate forms. These variations depend principally on the alternate extrusions of projectiles and of lava from the same vent, which leads to the building of compound cones, the most usual type; the location of the opening through which lava escapes, whether from the summit or through the side of a crater; the degree of fluidity of the lava, whether highly liquid or thick and viscous; and the size and shape of the fragments thrown out during explosive eruptions.

The extrusion of highly liquid lavas, as we have seen, leads to the building of mountains with very gentle slopes, as in the case of Mauna Loa; highly viscid lavas, on the other hand, sometimes congeal in nearly perpendicular cliffs, as in the case of some of the Mono craters, California, described later, but in such instances lofty mountains are not formed, owing apparently to the clogging of the conduits through which the lava is emitted.

Instances are cited by Judd,[2] in which lava so viscous that it refused to flow on reaching the surface, has been forced out from volcanic vents and congealed in obtuse, steep-sided columns, having a concentric internal structure. The form and structure of these peculiar elevations has been imitated by forcing a thick paste of plaster of paris, vertically upward through a hole in a

[1] G. F. Becker, "The Geometrical Form of Volcanic Cones and the Elastic Limit of Lava," in "American Journal of Science," 3d series, Vol. 30, 1885, pp. 283–293.

[2] J. W. Judd, "Volcanoes," pp. 125, 127.

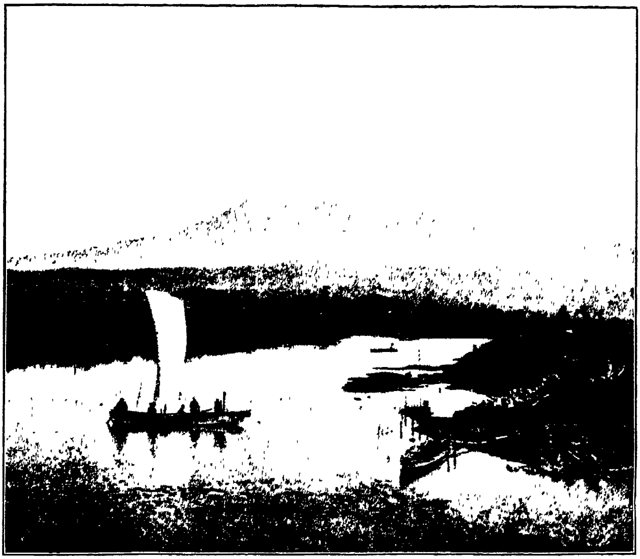


FIG. A. Fusiyama, Japan. A typical lapilli cone.

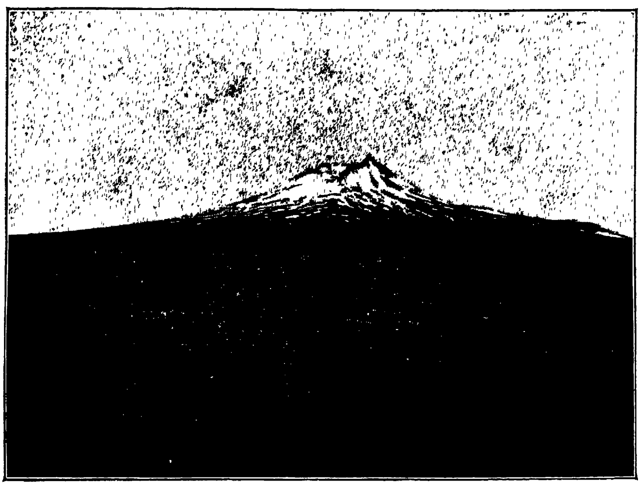


FIG. B. St. Augustine, Cook's Inlet, Alaska, 1895. (Photograph by U. S. Geological Survey.)

board. In the experiment, the layers first formed were raised and expanded by the paste which followed, so as to form an oval or bell-shaped mass, which, when cut through, exhibited an onion-like structure. Examples of hills of this nature are said to be furnished by many andesitic volcanoes in Hungary, certain phonolite hills of Bohemia, and more definitely by the so-called "mamelons" of the Island of Bourbon. Illustrations of the latter are given in the book just cited.

The most regular and by far the most beautiful cones, formed of projectiles, are such as are built up by the blowing out of fine dust and gravel-like fragments. The angle of repose of such material is less than that of rough scoria, and hence the sides of the cones formed of it are less steep than the slopes of cinder cones. When cinders are plastic at the time of their fall, they fuse together or adhere one to another, as in the case of the driblet cones of Hawaii, and form the steepest of all the various structures built about volcanic vents.

Structure of Volcanic Mountains

What arrangement of the material composing volcanic mountains would be revealed, if we could cut them from summit to base through a vertical plane and remove one half of the mass? The surface thus exposed would be a vertical section. Although it is not possible to obtain complete sections of this nature of such vast accumulations, yet volcanoes are sometimes breached by explosions from within, and variously dissected by erosive agencies acting from without. By studying the anatomy of volcanic mountains where thus exposed, we can learn many facts concerning their mode of growth.

Mountains formed of Lava Sheets.—Mountains made entirely of lava flows when dissected by erosion, reveal the edges of the imbricated layers of which they are composed. These, in normal instances, dip away from the crater and are of very irregular thickness. A sheet may have its maximum thickness near the vertical axis of the mountain or at a distance from it, depending on topographic conditions, the viscosity of the lava, and other causes. The overflows in the earlier stages of a volcano's growth are commonly from the crater, but as the mountain becomes higher, the force required to raise the liquid rock to the summit is increased, and relief is frequently found through fractures in the crater walls, aided perhaps by the melting of the rock of which the mountain is composed.

In undisturbed sedimentary beds the higher layers in a series are younger than those below. This is not an invariable rule, however, in the case of the imbricated sheets forming many volcanic mountains, since an eruption of lava may escape from beneath the margin of an older and previously hardened layer. What have been termed "imbricated mountains" by Powell, in which the surface layers have much the same arrangement as the tiles on a roof, the lower layers being the younger, have the structure here referred to.

The sheets of lava poured out in various ways so as to build up mountain masses, are not continuous all about the crater from which they were extruded, but in most instances are comparatively narrow streams radiating more or less definitely from the centre, which overlap at their margins and may even cross one another.

In exceptional instances, as already stated, lava is extruded in an extremely viscous condition, as is the case

of the "mamelons" of the Island of Bourbon, and rises into obtuse columns and dome-like forms, which have a concentric, onion-like structure, when seen in section.

Cones formed of Projectiles. — The structure of a volcanic pile composed wholly of material projected into the air during explosive eruptions, is strikingly different from that of mountains built wholly of lava sheets. As we have seen, the topographic form produced by scoria, lapilli, and dust falling about a volcanic vent, is that of a cone.

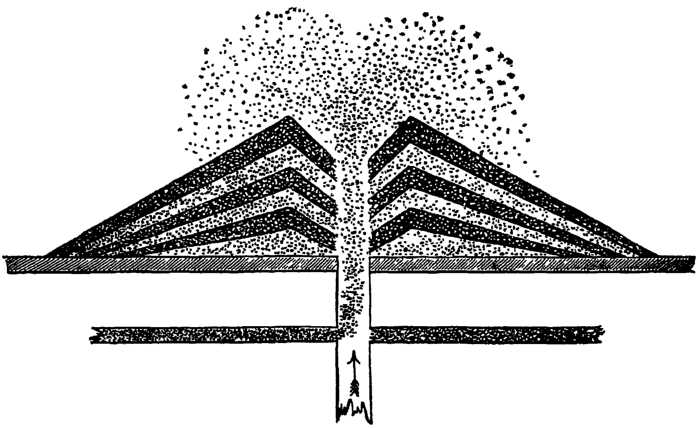


FIG. 3. — Experimental illustration of the mode of formation of volcanic cones composed of fragmental material. (After J. W. Judd.)

The arrangement of the layers in a vertical section of such an accumulation may be illustrated by a simple experiment.

If a tube is inserted from below, in a hole in the centre of a table, and sand, sawdust, and other similar material is blown through the tube by means of a bellows, it will rise from the opening and fall about it so as to form a conical pile, with a depression in its summit. If black and white material is alternately blown through the tube, a vertical section of the cone that is formed will have the structure illustrated in the above diagram.

The size of the cone obtained by such an experiment, the steepness of its sides, etc., will vary with the amount and character of the material used, and the strength of the air current; but the arrangement of the layers or their structure, exposed in a vertical section, will remain essentially the same. The layers are continuous all about the orifice, but are inclined in two directions from the rim of the central depression or crater. The pile has the appearance of being formed of two sets of cones, the smaller set being reversed and fitting into a hollow in the truncated summit of larger series. The inclination or dip of the inner layers is greater than that of the outer layers.

The arrangement illustrated above has been found to be characteristic of the structure of many volcanic mountains. In place of the mechanical regularity shown in the experiment, however, actual lapilli cones commonly exhibit marked irregularities, due to the blowing away of portions of their walls, and the subsequent filling of such breaches, and to variations in the intensity of the eruption which may admit of the building of a small cone with double slopes, within the crater of a larger structure. Some of the irregularities found in nature are shown in the following ideal action of Vesuvius.

Variations and irregularities also occur on account of the effect of the wind, and the inclination at which the projectiles start on their aërial journey. A lapilli cone in the region of the trade winds, for example, is usually found to be higher and more massive on the leeward than on the windward side. But in spite of all these modifying conditions, the lapilli cones in various stages of dilapidation that have been studied, exhibit in greater or less perfection the characteristic internal structure ob-

tained when analogous artificial cones are formed, as in the experiment cited.

Composite Cones. — Although mountains composed entirely of lava sheets, or made wholly of projectiles, may exist, the structures described as characteristic of such mountains are rather theoretical than illustrative of what one finds when the study of actual examples is undertaken. In the history of most volcanoes there have been times when lava has flowed down their sides, and again,

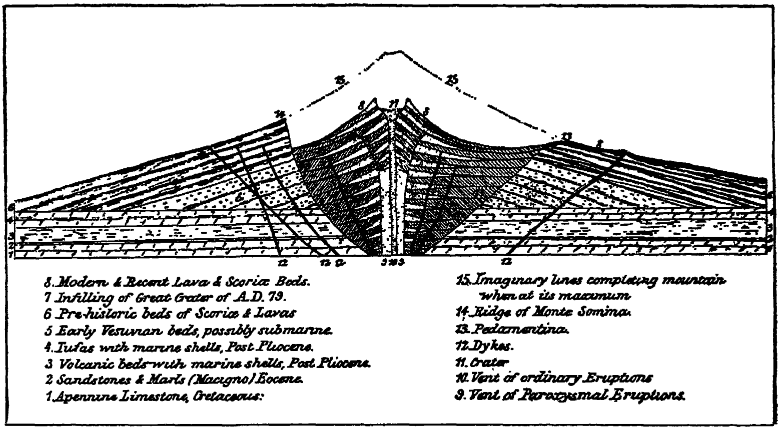


FIG. 4. Diagrammatic general section through Vesuvius at the present time, showing the structure, the substructure, and the successive accumulations. (After J. L. Lobley.)

periods when explosions have occurred and fragmental material spread over the previously formed lava sheets. Commonly, many such alternations in the character of the eruptions have occurred, and the mountains that result have a composite structure — sheets of lava alternating in an irregular way with layers of scoria, bombs, lapilli, and dust.

The slopes and contours of composite volcanic mountains are as varied as is their internal structure. When

lava flows predominate over the fragmental deposits, their shapes approach that of the typical flat-topped domes, of which Mauna Loa is an example; when the projectile material is in excess of the lava poured out in a fluid condition, cones with small apical angles and steep, concave sides, approximating to the form of Fusiyama, are produced. These contrasts are illustrated in Fig. 2.

It is the fate of mountains, inclusive of those of volcanic origin which escape destruction by explosions, to be slowly removed by erosion. During this process the secrets of their interior are revealed, and the nature of their internal structures controls the character of the topographic changes they pass through.

Dikes. — The structure of volcanic mountains, of whatever type, is subject to important modifications due to the opening of fissures and the injection into them of molten rock. The lava filling such fissures and hardening, forms sheets which may be vertical or horizontal or occupy any intermediate position, and in fact frequently change from one position to another that is quite different, in the same example. Such sheets of intruded lava which cut across the bedding of the rocks they invade are termed *dikes*.

The fractures formed in volcanic mountains frequently radiate from their centres, and occasionally cleave their sides from base to summit. Such fissures when filled with hardened rock add greatly to the strength of the piles they traverse, and furnish some of the most strongly pronounced topographic features when volcanoes are dissected by erosion.

The sheets of lava, scoria, and lapilli in composite volcanic mountains are frequently bound together by systems of dikes, which perhaps intersect one another. The

departures that volcanic mountains commonly present from the simple, ideal type of lava domes or lapilli cones depend therefore not only on the manner in which they are formed, but on subsequent internal changes. Still further complications arise when the molten rock, forced into fissures, reaches the surface and outflows, forming surface sheets, and when explosions, or basal melting, remove portions of a mountain.

Volcanic Necks. — The passageways or conduits leading to volcanoes from deep below the surface, and furnishing a passageway for the material erupted, are left filled with molten lava when the surface activity ceases; this material slowly cools and hardens into compact rock, and forms what are termed *volcanic necks.*

The conduits of active volcanoes may be completely filled with molten lava, as is the case when craters overflow. If the energy declines while a volcano is in this condition, its crater will have a floor of lava, which is the summit of a column or plug, the lower portion of which, perhaps miles beneath the surface, may be still in a highly heated and plastic condition. At other times, the liquid lava within a crater and in the upper portion of the conduit that leads to it, may be drawn off through fissures in the sides of the volcano, thus causing the surface of the lava column to fall to the level of the opening, leaving a more or less conical depression, perhaps two or three thousand or more feet deep. If the activity declines while the volcano is in this condition, the crater will remain as an empty bowl which, especially in humid climates, may become filled with water and transformed into a lake.

However diverse the conditions that attend the growth of a volcanic mountain, a core of lava occupies its centre

and approaches more or less closely to its summit. This column, cooling slowly under the pressure of its own weight, is changed to compact rock, which usually offers greater resistance to erosion than the material with which it is surrounded. In the old age of volcanic mountains, when their outer layers are decayed and washed away, these central cores frequently become prominent topographic forms. Fine examples of tower- and castle-like masses, marking the sites of ancient volcanoes, occur in many parts of the world. Particular attention will be given in a succeeding chapter to those of New Mexico.

Erosion of Volcanic Mountains

Geographers and geologists recognize two groups of forces or agencies, which, since the earth's surface was divided into land and water areas, have struggled with each other for the mastery. One of these groups of forces may be said to have its home in the interior of the earth, and tends to modify the surface of the globe by producing elevations and subsidences, and by igneous eruptions; the other group has its home in the air, and tends to modify the earth's surface in a variety of ways, but principally by weathering and erosion. The reservoir of energy in the case of the subterranean forces is in the residual heat of the earth; the external agencies derive their energy from the sun.

No sooner is a volcanic mountain upraised by subterranean forces than its removal and the transportation of its material to the sea is begun. The destructive work of the atmosphere never ceases, although it may vary greatly in intensity from time to time, until the mountain, perhaps presenting in its prime the most magnifi-

cent spectacle that has ever diversified the earth's surface, is cut away to the level of the sea.

The agencies by which such stupendous changes are brought about are slow in their action. Changes of temperature, by producing varying stresses in the rocks, cause them to become fractured, especially near the surface. Rain falling on the rocks flows away as rills and brooks which move the smaller fragments and by their friction cut channels in a mountain side. Water percolates through the porous rocks, and their more soluble minerals are dissolved. While the mountain is yet young this process of solution may be assisted by the residual heat of the rocks. Fresh volcanic rocks are especially prone to undergo chemical change, as the acid gases that accompany their extrusion and the more soluble solid constituents are dissolved by percolating water and add to its power as a solvent. When vegetation takes root on the once molten rocks as they cool, and as one generation of plants succeeds another, their decay adds organic acids to the water, and thus still again augment their solvent power. When water freezes in the interstices of the rock, its expansion acts as a powerful agent in promoting their disintegration.

By these and still other agencies, which for the most part act slowly and silently, even the greatest topographic changes resulting from volcanic eruptions are modified and finally removed. The combined action of all these various destructive agencies are comprised in what is termed *weathering* and *degradation.*

An interesting feature in the degradation of many volcanic mountains is seen in the fact that the seemingly weak and incoherent piles of scoria, lapilli, and dust,

which frequently form steep-sided cones, may withstand the attacks of the atmospheric agencies better than sheets of compact lava, when exposed to like conditions. The secret of this apparent anomaly is that the porous material absorbs the water supplied by rains, and allows it to percolate slowly away, thus robbing it of the power to erode the rocks by flowing over the surface and sweeping along fine débris. The removal of deposits of scoria, pumice, lapilli, dust, etc., is performed mainly by solution; at least until the insoluble residue left behind by partial decay fills the interstices of the portion remaining and surface streams become possible.

The drainage of lava sheets, unless fissured and broken so as to allow the surface waters to escape downward, is mainly by streams, which, becoming charged with small fragments, principally by the beating of rain, are enabled to carve channels for themselves. Many rills join to form larger lines of drainage; stream unites with stream to form rivers which flow away to the sea. Every stream, from the musical rill to the majestic river, is active in deepening its channel or broadening its valley. The steeper the slope, other conditions being the same, the more rapidly are the rocks ground away. Mountains are thus reduced to hills, plateaus are dissected, and hills and plateaus alike are reduced to plains. Such is the fate of a volcanic mountain although the march from topographic youth to maturity, old age, and death may be modified and lengthened by renewed eruptions or elevations produced by plutonic forces.

The main agencies which conspire to remove mountains may be grouped in two classes: *i.e.* mechanical wear and solution.

Rocks resist these two groups of agencies unequally; some are harder than others, some are more soluble than others. For these reasons largely, marked diversities appear as a volcanic mountain is slowly removed. One of the most conspicuous of these changes, especially in the case of a mountain composed without of scoria, lapilli, etc., and having a core of solid rock within, — formed by the cooling and harding of the lava occupying the conduit of the volcano, — is the removal of the incoherent external portion, and the uncovering of the central plug or "neck."

Signs of age in the case of a cone composed of scoria and lapilli, having a crater at the summit, are usually first made manifest by the decay of the rocks and the crumbling of the crater walls, due in part to the removal of particles by the wind, and the channelling of the lower slope of the mountain by streams. The rim of the crater at length disappears, the summit of the structure becomes blunted and forms a miniature plateau with a convex surface, due to weathering. As more and more of the summit is removed, rugged crags appear, due to the uncovering of the top of the column of dense lava within, or of portions of lava streams. The sides of the mountain become more deeply scored with radiating stream channels. The outer sheathing of loose material is slowly removed, principally in suspension and in solution by streams, but in part by the wind. As degradation progresses, the central core becomes more and more prominent, and at length stands as an isolated column, encircled by a sloping pediment of fragmental material — the wreck of the cinder and lapilli cone. In a more advanced stage of waste and decay, the central plug increases in height in reference to its immediate base, as the surrounding

surface is lowered, and then for thousands of years stands as an isolated tower, commemorating the memory of the volcano, of which it is the most enduring portion. Resistant as the central rocky core may be to both mechanical and chemical changes, it slowly yields, and, crumbling to dust or dissolved, in time — not centuries, but thousands of years — is removed, and in its place there is a plain, perhaps but slightly elevated above the sea. One may walk over such a plain without seeing so much as a mound to represent the mountain, perhaps snow-capped and glacier-crowned in its maturity, that was built by volcanic eruptions ages and ages before. The geologist studying such a region finds in the rocks the deeper roots of the vanished mountain.

During the series of changes outlined above, especially in the case of a volcanic mountain having a complex structure, many modifications in relief occur, besides those mentioned. Where the radiating lava sheets are thickest, pronounced ridges appear. Dikes are left in bold relief in much the same manner as in the case of the volcanic neck. Many other modifications of the process — dependent both on internal structure and composition, and on external or climatic conditions — have been described by those who have studied the life histories of topographic forms, but enough has been stated, perhaps, to interest the reader in the ever-changing expressions in the face of the earth, and lead him to look for these features during his travels.

Subterranean Intrusions of Igneous Rock

Volcanoes in numerous instances have a linear arrangement, and for this and other reasons are known, in many

localities, to be located on fissures in the earth's crust. In fact, there are many considerations leading to the conclusion that the positions of all volcanoes have been determined by fracture in the rocks through which their conduits pass. It is evident, therefore, that there is not only an intimate but a genetic connection between surface and subterranean igneous phenomena. In discussing this question it is of convenience to have in mind a distinction in nomenclature, commonly recognized by geologists, between molten magmas that cool at the surface and form *volcanic* rocks, and similar magmas that cool deep below the surface and form *plutonic* rocks. The rocks that are formed in the first instance are *ejected* or *extruded* at the surface, and in the second instance *injected* or *intruded* among older rocks below the surface. To illustrate: a fissure in the earth's crust which becomes filled with molten rock, usually by its being forced in from below under great pressure, may reach the surface and give origin to a volcano, or to a fissure eruption; the portion of the magma that entered the fissure but failed to reach the surface would in cooling form a dike. The same magma would thus form volcanic or plutonic rocks according to the position in which it cooled.

The conspicuous changes that volcanoes make at the surface attract such a large share of attention on account of the vast quantities of rock extruded, that the possibility of an equal bulk of similar material being injected into fissures and other openings in the earth's crust without reaching the surface is apt to be overlooked. In connection with the study of volcanoes it is instructive to have in mind some of the leading facts concerning these subterranean or plutonic intrusions.

Dikes. — The formation of sheets of igneous rock by the hardening of lava in fissures has already been mentioned in connection with the structure of volcanic mountains. Fractures in the earth's crust are not confined to the vicinity of volcanoes, however, nor to the immediate surface of the earth. They are known to affect many regions, no considerable land areas in fact being without such breaks, and to cut the rocks composing the exterior of the earth to a depth, in many instances, of tens of thousands of feet. The study of earthquakes has shown that some of the most severe shocks have been caused by the formation of rents in the rocks several miles in length and at a depth in certain instances of ten or twelve miles.[1] All fractures in the rocks are not widened into fissures, and only such fissures as penetrate to reservoirs of fused rocks or to regions where the rocks are sufficiently heated to pass into a plastic or liquid condition when pressure is relieved, become injected with molten magmas so as to give origin to dikes.

Igneous dikes,[2] then, are formed when fused magmas are forced into fissures, and on cooling and hardening form sheets of rock usually more or less vertical, which cut across the bedding of the strata they traverse. They may be composed of any variety of igneous rock that is rendered sufficiently plastic to flow under great pressure. It is probable, especially in the case of thin dikes, that they are formed quickly, as otherwise the cooling and hardening of the material first injected would retard the progress of the advancing sheet.

[1] J. Le Conte, "Elements of Geology," 4th ed., New York, 1896, p. 138.

[2] Dikes of another class owe their origin to the injection of sand or other similar material into fissures.

The rocks adjacent to a dike are usually altered in color and texture on account of the heat of the molten material injected into them. The intensity and lateral extent of this metamorphism vary according to the nature of the invaded strata, and the amount of moisture present. Many of the changes that are usually included under the term *contact metamorphism*, however, are due to the deposition of mineral matter, most commonly quartz, from heated waters that rise from below and follow the contacts of a dike with the adjacent rocks. Changes of this nature may continue long after the upper portion of a dike has cooled; the hot, mineral-charged water being derived from still highly heated regions below.

The molten rock forming dikes cools most rapidly at the surfaces of contact with the containing rocks; hence their sides are frequently much finer in texture than the central portions, where cooling progresses more slowly and larger crystals are formed.

As in the case of lava flows, the molten rock injected into fissures frequently acquires a columnar structure on cooling, owing to contraction and the formation of joints. The rock is then divided into prisms most frequently six-sided, which are arranged at right angles to the cooling surfaces. This *columnar structure*, or *basaltic structure* as it is sometimes termed, since many of the finest examples occur in basalt, is frequently well marked, and when the dikes are exposed by weathering, gives origin to striking peculiarities, as may be seen from the accompanying illustration of a dike, brought into relief by the removal of the enclosing rocks, that occur on the shore of Lake Superior.

Instead of a well-defined series of joints dividing a

dike into columns, the rock sometimes has a concentric structure which becomes apparent on weathering. As decay advances, the irregularly jointed material, uniting the more compact spherical masses, is first removed, and *boulders of disintegration* become the most prominent features of the exposed edge of the dike.

The influence of decayed and disintegrated dikes on topography is varied, and depends on the chemical and

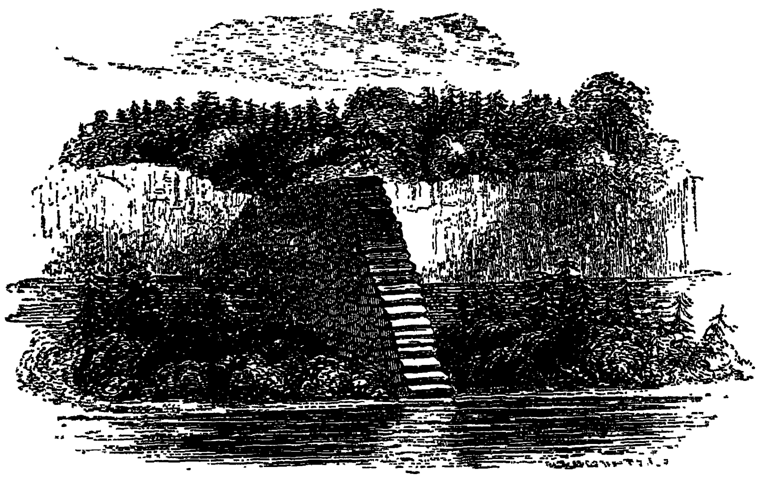


Fig. 5. Columnar dike, shore of Lake Superior. (D. D. Owen.)

mineralogical nature of the rock composing them; on their jointed or concentric structure; on the nature of the enclosing rock, whether harder or softer, or more or less soluble, than the dikes themselves; on the nature of the climate to which their outcrops are exposed; and on the nature of the erosive agencies, whether mainly mechanical or in a great measure chemical, etc. At times dikes produce prominent ridges, and again are deeply decayed and their material removed in solution so as to give origin to depressions. These varying results, which sometimes

enter largely into the scenery of a region, cannot be considered further at this time, since they pertain more strictly to a study of the origin of topographic forms than to the consideration of the nature of igneous intrusions.

Intruded Sheets.— Dikes, as we have seen, are produced by the injection of molten rock into fissures. When fissures reach the surface and lava rises through them and flows over the adjacent country, subaërial or *extruded* sheets are formed. It has frequently happened, however, that molten rock instead of gaining the surface, has been forced in between layers, usually of sedimentary origin, in such a way as to separate them and make room for itself by raising the rocks above, and spread out so as to form *intruded sheets*.

The distinction that is recognized between a dike and an intruded sheet, is, that the former occupies a fissure *which breaks across the bedding of the enclosing rocks*, while the latter *is conformable with the bedding of the adjacent rocks*. Probably all intruded sheets, if traced toward their source, would be found to pass into dikes. That is, the magma forming an intruded sheet rises from deep within the earth through fissures, until it reaches a horizon where the rocks are no longer fractured, and is then forced in between the strata. If such a sheet should meet another fissure, the course of the injected material might be again changed, and, following the break, again form a dike.

The statement that intruded sheets lie between strata of sedimentary rock needs to be qualified, inasmuch as intruded sheets might be formed between layers of igneous rock.

Surface lava flows, so long as they remain uncovered by later deposits, are not to be mistaken for intruded

sheets, although such an error might arise when an intruded sheet is revealed by the removal of its covering. When surface flows are buried beneath sedimentary layers, it is evident that in a general way they would simulate intruded sheets. A crucial test by which the two may be distinguished, is, that an intruded sheet produces more or less metamorphism in the rocks both above and below it, while an extruded sheet, having no rocks above it to be altered by its heat, only produces a change in the subjacent layers. There are many other occurrences which may guide one in determining whether a layer of basalt, for example, exposed in the sides of a ravine or canyon, with sandstone, shales, etc., both above and below it, was intruded into its present position after the associated sedimentary beds were laid down and hardened, or whether it was originally a surface sheet, subsequently covered by sediments. Among the differences to be looked for are the structure of the surface of the sheet of basalt, whether scoriaceous, as is the case with the surfaces of lava sheets that cool under atmospheric pressure, or compact and fine grained like the sides of dikes and similar to both the upper and lower surfaces of intruded sheets. The presence of pebbles of basalt in the rocks resting on the igneous sheet might also show that the superior beds were formed after the igneous rock had cooled. Still other indications of value to the field geologist in interpreting the history of such occurrences as just cited, may be found in most books on physical geology.

Intruded sheets, like dikes, vary greatly in their dimensions, and in the amount of energy that they represent. At times their thickness is to be measured by tens of feet, or even by inches, and again by hundreds of feet;

this superficial extent is sometimes hundreds of square miles. One of the most remarkable instances in North America of the magnitude which intruded sheets may attain, is furnished by the Palisade trap sheet of New Jersey and New York, the edge of which forms the picturesque Palisades of the Hudson. This sheet was intruded into the sandstones and shales of the Newark system, and has a diameter from north to south of not less than seventy miles. The minimum width of the portion which remains, its eastern extension having been removed by erosion, is about two miles; its thickness varies from 300 or 400 at Jersey City, to 850 feet in the Hook Mountains of Rockland County, New York.[1]

One essential condition for the formation of widely extended intruded sheets is that the receiving terrane shall be composed of nearly horizontal strata. On account of the weight to be lifted in order that an intruded sheet may make room for itself, it is evident that intrusions of the nature here considered are possible only in the upper portion of the earth's crust. The absence of fractures in the invaded strata is shown by the fact that the injected molten rock does not escape through fissures and form dikes and surface overflows.

Plutonic Plugs. — It is instructive to notice at this time a class of topographic features which have a striking resemblance to volcanic necks, but are of a different origin. In some instances, intrusions of plutonic rock, instead of forming dikes or spreading out in sheets, rise through sedimentary beds for some distance and then,

[1] I. C. Russell, "The Newark System," U. S. Geological Survey, Bulletin No. 85, pp. 74–76. N. H. Datton, "The Relations of the Traps of the Newark System," U. S. Geological Survey, Bulletin No. 67, pp. 37–53.

without expanding, lift the strata above so as to form a dome. When erosion removes the dome of stratified rock, a plug of igneous rock is exposed within. These plug-like intrusions unaccompanied by a lateral spreading of the magma, it is convenient to designate as *plutonic plugs*. Several instances of such local intrusions into nearly horizontal sedimentary strata are known in the neighborhood of the Black Hills of Dakota. On the northwest side of the Black Hills a remarkable series of elevations occurs, which range from a regular dome of stratified beds in which erosion has not cut deep enough to reveal the plug below, through several examples in which a prominent tower-like mass of igneous rock a few hundred feet high rises in the centre of concentric ridges formed by the truncated edges of hard layers in the base of a deeply eroded dome, to a still more prominent column over six hundred feet high, from about which all remnants of the stratified rocks that formerly arched over it have been removed. A description of these unique topographic features and certain general conclusions that their study has suggested, have been given elsewhere.[1]

Laccolites. — Intermediate in both form and size between intruded sheets and plutonic plugs are certain igneous intrusions that after rising for a distance through stratified beds, expand between the layers not so as to form widely spread sheets, but in thick masses which raise the rocks above into domes. These plugs or dikes with expanded summits are termed *laccolites*, or stone cisterns.

[1] I. C. Russell, "Igneous Intrusions in the Neighborhood of the Black Hills of Dakota," in "The Journal of Geology," published by the University of Chicago, Vol. 4, 1896, pp. 23–43.

Typical examples of intrusions of this character form the Henry Mountains in southern Utah. Six or seven thousand feet of strata have there been eroded away, leaving the hard resistant cores of the former domes exposed. In some instances these cores are 12,000 feet or more in diameter, and 5000 feet thick, in the central part. As they stand to-day after ages of decay and erosion, they form picturesque mountains which rank among the more important isolated uplifts of the United States.

Since the nature of laccolitic mountains was first pointed out by Gilbert[1] many other occurrences of the same nature have been recognized in America and other countries.[2]

Subtuberant Mountains. — The nature and magnitude of the injections termed laccolites, prepares us to take still another step in unravelling the complex changes produced in the earth's crust by molten magmas forced in from below.

The domes formed by plutonic plugs are in known instances from a mile to two or three miles in diameter; the domes elevated by several of the larger laccolites that have been studied must have been from five to ten miles in diameter. Forcibly as these dimensions impress one, they become of a secondary order of magnitude when compared with similar measurements of still other dome-shaped uplifts that occur in the central portion of the United States.

1 G. K. Gilbert, "Report on the Geology of the Henry Mountains," Geographical and Geological Survey of the Rocky Mountain Region. Washington, D.C., 1877.

2 Whitman Cross, "The Laccolitic Mountain Groups of Colorado, Utah, and Arizona," U. S. Geological Survey, 14th Annual Report, 1895, pp. 157–241.

The Black Hills of Dakota owe their present form to the sculpturing of a vast dome which if remodelled would have a diameter from northwest to southeast of 160 miles, and at right angles to this direction, of eighty miles, and a height above the surrounding plain of about 7000 feet. This great dome has been deeply dissected. The hard layers in its basal portion form concentric rings about a central core of granite. The dip, or inclination, of these upraised layers is away from the vertical axis of the dome in all directions. Completely encircling the outer ring of the truncated dome are horizontal strata for scores of miles, of the same nature as those affected by the uplift. That is, in the central portion of a vast plain, underlain by thousands of feet in vertical thickness of horizontally stratified sandstones, shales, and limestones, resting on metamorphosed rocks, there has been an uplift produced by a force acting from below directly upwards, which has raised the strata into a dome a mile and a half in height above its immediate base.

The Big Horn Mountains of Wyoming have the same general structure as the Black Hills, but the dome from which they have been sculptured was much larger. In central and southern Wyoming and in Colorado there are still other uplifts of the same nature as those just mentioned, which furnish evidence of having been sculptured from vast domes that exceed in size those that rose to form the Black Hills and Big Horn Mountains.

These domes, rising as they do in a broad region of horizontally bedded rock, and having the upraised layers dipping away in all directions from a central region, are not of the nature of folds produced by a lateral thrust, as in the case of the Appalachian Mountains, for example,

but owe their origin to a force acting from below upwards. Their analogy in form and structure to the domes raised above plutonic plugs and laccolites leads to the inference that they owe their origin to igneous intrusions. Without restating all the arguments that lead to this conclusion, I can say that a plausible hypothesis in reference to the origin of uplifts of the type of the Black Hills, is, that they may have been elevated by molten magmas forced into the earth's crust, deep below the surface. The enlargement of these deeply seated bodies of intruded rocks may be likened to the growth of a tuber in the earth; as a convenient name for uplifts originating in this way, I have suggested the term *subtuberant mountains.*[1]

Generalizations.—The study of volcanoes and of subterranean intrusions of igneous rock, has shown that the two are the result of the action of the same series of forces and are in reality but varying results of a single process. A proper understanding of the nature of volcanoes cannot be reached without taking into consideration the manner in which injections of molten matter into the earth's crust have been produced.

The nature of subterranean intrusions leads at once to the conclusion that steam cannot be considered as the propelling force which injected molten magmas into other rocks already cold and solid. By thus going to the roots of the volcanoes, as it were, the theory that steam is the primary force which gives origin to volcanoes is removed. It becomes apparent also from the study of intrusions that

[1] The nature and origin of subtuberant mountains and their relation to plutonic plugs, laccolites, intruded sheets, and dikes, have been discussed by the writer in "The Journal of Geology" (Chicago), Vol. 4, 1896, pp. 177–194.

the origin of the heat which causes the fusion of rocks deep below the surface, and the origin of the pressure which causes the magmas thus formed to rise in fissures and lead to the formation of various classes of intrusions and to volcanoes, are distinct and should be separately considered.

What may be considered as a continuation of the lines of thought here suggested, will be found in next to the last chapter of this book.

Characteristics of Igneous Rocks

The rocks of which the earth's crust is composed present great diversity. In order to avoid confusion from the endless variations they exhibit, it is convenient to classify them first of all in three great groups: namely, *igneous*, *sedimentary*, and *metamorphic* rocks. This may be considered the general order in which the rocks were formed since the first crust of the earth, under the most plausible hypothesis that has been presented, was produced by the cooling of fused material. Where this primal crust rose above the sea, it was disintegrated and worn away so as to furnish material for sedimentary beds. At a later date, both volcanic and sedimentary rocks were in many localities intensely heated and underwent great mechanical, chemical, and mineralogical changes, which led to marked alterations in all of their characteristics. These altered rocks are said to be metamorphosed. They constitute the third great group mentioned above.

In the restricted view of nature presented in these pages, we have but little to do with sedimentary and metamorphic rocks, and will therefore find it most advantageous to concentrate our attention on some of the leading char-

acteristics of the rocks which were once in a state of fusion and have cooled and crystallized from a molten condition.

An idea of the general nature of igneous rock, but more especially of those which have been thrown out by volcanoes and cooled on the earth's surface, may be obtained by watching the slag as it is drawn from an iron furnace. In order to obtain metallic iron, iron ores are placed in a furnace, together, usually, with limestone and charcoal, coal, or other fuel. The combustion of the fuel produces sufficient heat to fuse the charge, and chemical changes lead to the separation of the iron from the slag. The slag is really fused rock, which is lighter than the molten iron and floats on its surface. When an opening is made at the proper place in the furnace, the slag flows out as a stream of liquid matter which, if sufficiently heated, will run on a gently inclined slope almost as freely as water. Usually, however, the slag is not so highly heated, and flows sluggishly. Such a stream of molten slag imitates many of the phenomena to be seen when a volcano discharges a stream of lava. The slag cools quickly at the surface and forms a crust, which floats on the still highly heated portion below. The division between the surface crust and the still fluid stream beneath is not usually well marked, but one grades into the other. As the still fluid portion continues to flow, the stiffened crust above is dragged along with it and is wrinkled and acquires a corrugated surface similar to that of certain lava streams. But little steam escapes from the slag at first, but in flowing over moist sand or earth, clouds of vapor rise from it. An analysis of this steam would show that various gases are mingled with it. Owing to the rapid

cooling of the slag some of the steam and accompanying gases are retained and, expanding, form bubbles which leave cavities in the hardening mass. When the slag is of the proper consistency, it is so completely filled with such steam cavities as to be froth-like, and on cooling forms a substance much like pumice. If we break a cake of slag, we will usually find that the upper surface contains many more bubbles, or, in other words, is more scoriaceous, than the central portion. In all these features an analogy with the behavior of a lava stream will be noted. Still further: if the slag is allowed to cool in thin sheets without a surface covering, it will form a glass-like material; if it cools more slowly, a stony texture is produced; if covered with a layer of dry sand or earth a foot or two deep, thus confining the heat and allowing the fused mass to cool still more slowly, various crystals will develop. All the varieties of slag from the glassy form which has cooled too quickly for crystals to appear, through the stony material in which crystallization has been arrested before well-shaped crystals have formed, to the varieties in which more or less well-defined crystals may be distinguished, may be duplicated from a collection of the products of volcanoes.

If we grind small flakes of slag and of the lava that most nearly agree with them in texture, until they are sufficiently thin to transmit light, we will find on examining them with a microscope that their similarities, in many cases, extend to their minute internal structure. A feature of special interest, in such a comparison, is that the slag that has cooled slowly and volcanic rock with a similar texture, consist of a glassy base through which more or less perfectly formed crystals of various minerals are

scattered. By careful selection, a series may be obtained both of slag and lava, passing from nearly clear glass on one hand, through varieties in which but few crystals are enclosed, to more perfectly crystallized material in which well-formed crystals exceed in bulk the glassy base which unites them.

Such a comparison of slag and lava as has just been suggested, furnishes strong evidence that many of the characteristics of volcanic rocks have resulted from the conditions under which they cooled. By varying the composition of slag, or by studying the products of various kinds of furnaces, such, for example, as those in which copper, silver, and other ores are smelted, it may be shown that some of the various physical features they present depend on their chemical composition. The same is true, as has already been stated in speaking of acid and basic rocks, of the lavas extruded by volcanoes.

Reverting for a moment to the question of the ultimate causes of volcanic eruptions, we recognize the fact that the origin of the heat in a furnace, and nature of the force which causes the slag, etc., to flow out, are distinct and separate. Although some steam may escape from molten slag, no one will consider that it is the force of the imprisoned vapors and gases that causes it to flow. As I hope to make clear in discussing the theories that have been advanced to account for the behavior of volcanoes, there does not seem to be sufficient evidence to show that the steam imprisoned in lava is the main or essential cause of its rising in the conduit of a volcano and overflowing. However, let us pass this consideration until we have a large body of well-established facts in hand, on which to base theoretical deductions.

As we have seen, volcanic eruptions may be divided in a general way into two groups, — the quiet and explosive. It is to be remembered, however, that these are the extremes of a series, between which there are many gradations. Let us see if these two types of eruptions can be simulated by the behavior of the slag drawn from a furnace. The quiet flow of a stream of slag when an opening is made at the right time and at the proper level in a furnace, is evidently analogous to the quiet extrusion of lava from certain volcanoes. If, however, the molten slag meets with a pool of water, a steam explosion will follow. Steam will be generated with great rapidity and form a conspicuous cloud, and possibly a sharp explosion will result from the ignition of the gases produced. Fragments of slag will be projected into the air and fall on neighboring surfaces. On examining the fragments of slag, we will find that they are mostly scoriaceous, and in some instances froth-like; evidently the steam has found its way into the still plastic magma and expanded it. The lesson suggested by such an experiment evidently is, that if the lava when forced up in the conduit of a volcano comes in contact with sufficient water, an explosion will follow, and also that the steam generated may in part become intimately commingled or occluded in the molten rock. Variations in the amount of water, or in the pressure of the lava at the locality where steam is formed, the consistency of the lava, whether highly liquid or viscous, etc., will manifestly vary the results.

A study of the behavior of slag suggests a trial hypothesis in reference to the causes of the marked variations in volcanic eruptions. Not only are we led to infer that the source of heat which fuses igneous rocks, and the source

of the pressure which causes the liquid lava to rise to the surface, are distinct, but that the steam which forms such a conspicuous feature more especially of explosive eruptions, has a different origin from the heat and initial or primary pressure, and is of a secondary nature, due, we may say, to the accidents that the rising lavas meet with on their passage to the surface.

Classification of Igneous Rocks based on Physical Characters.— Rock material in a state of fusion, whether highly fluid or pasty and viscous, is termed a *magma.* Such magmas on cooling produce *igneous* rocks; this being the comprehensive name to include all rocks that have cooled from a state of fusion. The subdivision of igneous rocks into *volcanic* and *plutonic,* already referred to, is now generally recognized; the distinction being based on the conditions under which the magma cooled. Molten rock which reaches the surface or sufficiently near the surface to be practically relieved of pressure except that of the atmosphere, falls in the class of volcanic rocks. Most of the solid material erupted by volcanoes belongs in this division.[1] The molten rock forced into fissures, or forming intruded sheets, laccolites, etc., which cools below the surface, constitutes the great group of plutonic rocks. As we have already seen, many secondary phenomena, such as the scoriaceous structure of volcanic rocks, the compactness of plutonic rocks, etc., go with the conditions under which magmas cool. But the essential distinction between volcanic and plutonic rocks refers to the position reached by a magma at the time of cooling, and no defi-

[1] The exceptions are when fragments derived from the sides of the conduits through which lava issues are thrown out by volcanoes; as in the case of the limestone blocks found on the crater of Vesuvius.

nite line can be drawn between the two. The material in the upper portion of the conduit of a volcano forms a volcanic rock, while material of the same character which failed to reach the surface but cooled under pressure, gives origin to a plutonic rock.

The rate at which a magma cools also leads to well-marked differences in the resulting rock. Rapid cooling, as in the case of most furnace slags, prevents crystallization, and glassy rocks are produced. The type of such a rock is the black volcanic glass known as *obsidian.* Such rapid cooling is seldom possible except in the case of magmas extruded at the surface, hence obsidian and related rocks are only found among the products of volcanoes.

When a magma cools less rapidly than in the case when volcanic glass is produced, minute crystals spring into existence, which float in the still fused material. If solidification takes place at this stage, the ground mass becomes a glass or *felsite,* and scattered through it are minute and more or less well-defined crystals. Still slower cooling admits of a larger portion of the magma becoming crystallized, and in the great majority of igneous rock we find multitudes of crystals of various minerals, united by a comparatively small quantity of felsitic material. As variations in the rate of cooling occur in both volcanic and plutonic rocks, it is evident that in each case rocks of various mineralogical composition may occur.

A basis for still further distinctions in structure is found in the degree of crystallization that has taken place. Rocks in which only minute crystals are scattered through a felsitic base, are designated as *cryptocrystalline;*

when the crystals are large enough to be seen to some extent by the unaided eye, they become coarsely crystalline or *macrocrystalline*. In many instances conspicuous crystals from perhaps half an inch to one or two and even more inches in diameter are developed; the rock is then said to be *porphyritic*, in reference to the fact that a large class of rocks formerly designated as porphyries had this characteristic.

Classification of Igneous Rocks based on Chemical Characters.—Igneous rocks also differ widely among themselves in reference to chemical composition, and attempts have been made to classify them on this basis. Large numbers of chemical analyses have been made which show that they are diverse in composition, and probably contain all known elements. These elements almost always exist in combination, the most common being silicates of alumina, magnesia, lime, potash, and soda, frequently with the addition of magnetic iron and phosphate of lime. On classifying many analyses of igneous rocks, it becomes apparent that they fall in two somewhat well-defined groups, in reference to the amount of silica they contain. In one group the silica present, considered as an acid, has been sufficient to satisfy all the bases; in the other group the silica is in excess. On this plan of classification, as has already been stated, the rocks containing sixty-six per cent or more of silica are termed *acid rocks;* and those containing about fifty-five per cent or less are designated *basic rocks*.

The acid rocks, on account principally of the preponderance of highly silicated feldspar present, are usually light colored; while basic rocks, principally on account of the abundance of iron-bearing minerals, are dark rocks. The

specific gravity of acid rocks in general is less than that of basic rocks; the specific gravity of the former, as a rule, ranging from 2.3 to 2.7, and the latter from 2.7 to 3.1.

With only a few analyses of igneous rocks at hand, it might be found that their classification into acid and basic would be somewhat sharply defined. With a large number of analyses available, however, especially of rocks from numerous localities, it will usually be found that a selection can be made which will show a somewhat complete gradation from typically acid to typically basic examples. To meet this difficulty an *intermediate* group, to include such rocks as are not decidedly acid or basic, has been proposed. Ultra-acid rocks are such as contain a high percentage of free quartz.

The classification of rocks on a chemical basis, as just described, is not confined to those of igneous origin, but may be made to include metamorphic and even sedimentary rocks as well.

Characteristic examples of acid rocks are furnished by granite and the light-colored igneous rocks, known as rhyolite, trachyte, etc. Ordinary obsidian and pumice also fall in this group. The basic rocks are typically represented by basalt, and allied rocks which are characteristically dark and heavy. The rocks mentioned in this paragraph are briefly described a few pages in advance.

Classification based on Mineralogical Characters. — The slow cooling of a magma, as we have seen, is accompanied by the crystallization of the substances it contains. If the cooling is rapid, a *crystalline* glass is produced, but not well-defined individual crystals. The slower the cooling, the greater the opportunity for the molecules of various

substances to arrange themselves in the definite forms we term *crystals*. While the size of the minerals thus formed is regulated mainly by the rate of cooling, their composition depends on the elements present in the magma and on their relative proportions and on other conditions. Hence the minerals composing igneous rocks may be taken as a basis for their classification.

In porphyritic and macrocrystalline rocks, the mineralogical composition can frequently be determined by the unaided eye, or by the use of a simple magnifying glass, but a more satisfactory method and one indispensable in the examination of cryptocrystalline and glassy rocks, is by means of a microscope. For this purpose thin flakes are struck off from a rock with a hammer, or obtained by sawing it into thin sheets by means of a revolving metal disk charged on the edge with an abrading substance like diamond dust. These flakes are then ground, usually with emery, until sufficiently thin to transmit light, and mounted in Canada balsam on a strip of glass.[1]

When thin sections of igneous rocks are examined under a microscope, a low power being usually the most satisfactory, it will be seen that in the majority of instances they are composed of crystals of various minerals embedded in a glassy or cryptocrystalline base or ground mass. Of all but the most minute crystals, only sections are seen; that is, the pellicles of rock are so thin that

[1] Instructions for preparing rock sections for microscopical examination, as well as descriptions of the optical properties of minerals, the characteristics and classification of rocks, etc., are given in many books on petrology. Among those usually most accessible are: Frank Rutley, "The Study of Rocks," New York, 1879. J. W. Judd, "Volcanoes," New York, 1881, pp. 59–66. H. Rosenbusch, "Microscopical Petrography," translated by J. P. Iddings, New York, 1889. E. H. Williams, "Manual of Lithology," New York, 1895. J. F. Kemp, "A Handbook of Rocks," New York, 1896.

only slices cut from the various minerals contained in them are obtained. The slices of crystals reveal various outlines according to the direction in which they are cut. The identity of the minerals is determined in part from the shapes of these cross-sections. A section of a quartz crystal, for example, cut at right angles to its longer axis, will reveal a hexagonal figure; a cube of iron pyrite will give a rectangle, if cut parallel to any axis, etc. Combined with a petrographic microscope is a polariscope. As minerals transmit light in accordance with the arrangement of their molecules, the crystallographic systems to which they belong may in most instances be determined by the changes they produce in polarized light.

It is impossible in the space at command, to give anything like an adequate outline of the methods used in determining the minerals of which rocks are composed by the modern petrographic methods, or of indicating the schemes for classifying rocks based on such studies. I wish to say, however, that the student who uses the microscope in connection with the field study of rocks, has a most interesting and really fascinating path of inquiry open before him. The beauty of many of our most common rocks when ground sufficiently thin to transmit light, and examined by means of polarized light, is truly surprising. The colors that blaze forth when sections of feldspar and many other common minerals are examined in this way, and the changes of color produced when the polarizer is revolved, are beautiful beyond all conception. The most gorgeous harlequin opal becomes pale and lustreless in comparison with the rainbow tints seen in the light that has passed through a section of a wayside pebble. The microscope not only reveals the minute

organisms of a formerly unseen world, but has made the very stones write their histories in characters of light. Nor are these gorgeous displays mere play to fascinate the eye. Some of the most profound problems that the geologist meets with in reference to the origin of rocks, and the many changes they have undergone, have been successfully attacked by this modern method of detailed and painstaking study. Field explorations during which the character and relation of great bodies of rock are investigated, should be followed by laboratory study of selected samples, embracing chemical analyses, microscopical investigation, etc. This combination of the study of rocks as they occur in the crust of the earth and their more special characteristics as revealed in the laboratory, is termed *petrology*.

The classification of rocks based on their mineralogical composition, is too extended and too technical a subject to be introduced at this time. Some few facts concerning this branch of geology, however, and a brief description of some of the more common igneous rocks, will assist the student in reading the account of the volcanoes of North America which follows this introductory chapter.

A classification based on the microscopical structure of igneous rocks adopted by certain petrographers, recognizes three leading types of micro-structure; namely, *granular*, *porphyritic*, and *glassy*. Other students claim that two stages of crystallization may usually be recognized, the first characterized by the growth of large crystals in a still molten magma, and the second by the formation of much smaller crystals which are arranged about the members of the older series. In some rocks the former, and in other rocks the latter, of these two phases of crystal-

lization predominates. Two leading classes of rocks are thus recognized: 1st, the *holo-crystalline* or *granitoid* rocks, the type being granite, composed of crystals belonging to a single epoch of crystallization, but in which neither an amorphous ground mass, nor crystallites (small, undeveloped crystals) are present; 2d, the *semi-crystalline* or *trachytoid* rocks (the type being trachyte), distinguished by a more marked contrast between the crystals of the first and second periods of consolidation, and the presence usually of an amorphous ground mass in which the crystals are embedded. To these a third and subordinate class is sometimes added to include such rocks as are composed wholly of glass, without embedded crystals.

Under each of these family groups several genera, as they may be termed, and numerous species have been recognized. A few of the most common genera are noticed below. The first, granite, will serve as a representative of the great class of wholly crystalline rocks to which it has given a name; while the others, basalt, rhyolite, trachyte, and andesite, will stand for the equally great, and yet more diversified, class of semi-crystalline rocks.

Granite.— The great diversity in color and texture of the rocks of this type is probably familiar to the reader from the many varieties used for monumental and architectural purposes. Its color varies through many gradations from dark gray or nearly black, to pink and red, according to the predominant mineral constituent. The minerals composing granite are quartz, feldspar, and mica, but many times accessory minerals occur in abundance. The quartz is readily recognized from its resemblance to

clear glass, its hardness (it will scratch glass), and the fact that it is without cleavage; that is, it will break in one direction as readily as in any other, the surfaces of fracture being uneven. The feldspar varies from white to pink in color, and cleaves easily along certain parallel planes, producing smooth brilliant surfaces. It is softer than quartz, can be scratched with a knife, but will not scratch glass. The mica splits easily into thin plates or scales, which are elastic. It is softer than the feldspar, and frequently dark in color and even black.

If one examines a piece of polished granite either with a pocket lens or a microscope, it will be found that with the possible exception of certain accessory minerals, it is composed of more or less perfect crystals of the three minerals described above, which interlock with one another in almost all instances without an intervening glassy or micro-crystalline ground mass; that is, all of the substance present has been crystallized—the rock is holocrystalline. Recent studies have shown, however, that while nothing like a vitreous ground mass can be discovered, certain granites do contain a minutely crystalline ground mass, in which the larger crystals are embedded. This illustrates the fact that even the larger groups into which rocks are divided are really artificial; in reality, there is no sharp division between holo- and semicrystalline rocks. Their crystalline condition depends largely on the rate at which they cool. Between those which cool so slowly that all the material present passes to a crystalline condition, and those which cool more rapidly, but yet harden before all of the material present has assumed definite crystalline forms, there must of necessity be a complete gradation.

While granite does not occur in the condition of a surface flow and is not known to have been produced by volcanoes, it is found abundantly as bosses and dikes and forming vast masses which were intruded in a molten or plastic condition among other rocks, and now exposed by deep erosion. It also occurs as the surface rock over vast areas, where, again, great erosion has taken place. In such instances it is sometimes found to pass on its border into gneiss and schist and other rocks that are termed metamorphic; that is, it passes by insensible gradations into rocks usually of sedimentary origin, that have been changed by pressure, heat, and the passage through them of heated waters, into a crystalline condition. These metamorphic beds, again, when examined at a distance from the granite, are sometimes found to pass by insensible gradations into ordinary sedimentary strata like shale, limestone, etc. In such instances it is plain that the gneiss and schist have been formed by the alteration of sedimentary beds, and the inference is that the granite is but another step in the same process.

Granite also occurs in the axes of many mountain ranges, where elevation and deep erosion have taken place. Occasionally the side of a fracture in the earth's crust has been upraised, perhaps many thousands of feet, so as to expose granite as the basal member of a great series of rocks. It appears, therefore, that granite may be either an igneous or a metamorphic rock. Igneous, when it has been in a state of fusion and allowed to slowly crystallize; and metamorphic when the original material changed to a crystalline form without complete fusion. Between the two processes there is a complete gradation, and no one can say where the boundary line should be

drawn. To which class a sample of granite belongs can only be determined by field study, and even then a definite answer cannot always be obtained.

Granite as a rule decomposes when exposed to the action of the atmosphere, with comparative ease. The feldspar yields to solution. The quartz is broken by changes of temperature, etc.; the mica separates into flakes and scales. These surface changes frequently extend to a depth of one or two hundred feet. When the decayed rock is within the reach of streams, it is washed away and its various ingredients assorted, and in many cases deposited separately. The decomposed feldspar forms clay, some of which is pure white and known as kaolin or china clay; the quartz forms sand, in which spangles of mica commonly occur.

Basalt.—Next after granite and allied rocks, the most abundant crystalline rock that the student of the earth's history is apt to meet, is basalt and its near relatives. Familiar examples of the occurrence of basaltic rocks are furnished by the Palisades of the Hudson; Blomidon and North Mountain, Nova Scotia; Mts. Holyoke and Tom, Massachusetts; the Columbia lava of Oregon, Washington, and adjacent states; the products of the Hawaiian volcanoes; the columnar rocks of the Isle of Staffa, Scotland, and the Giant's Causeway, Ireland, and at many other localities.

Basalt is normally a dark, heavy rock, varying in compactness from scoria filled with steam cavities, to a dense material without visible apertures. It varies, also, in texture from coarsely crystalline, when distinct crystals are visible to the naked eye, to cryptocrystalline, and in some instances is a compact black glass with perhaps

minute, immature crystals. The minerals composing it are essentially feldspar, augite, and magnetite. The feldspar is most abundant, and is usually the species known as *labradorite*, which, like nearly all of the group to which it belongs, is essentially a silicate of alumina, but is comparatively poor in silica. Other and more highly silicated feldspars, however, may take the place of the labradorite or be associated with it. The light-colored crystals to be seen in coarse-grained basalts are feldspar; sometimes two varieties may be distinguished by the unaided eye. The augite and magnetite are dark minerals, the magnetite being always black, and give to the rock much of its sombre tone. With these more essential minerals, others, such as olivine, leucite, mica, garnets, etc., may be developed as accessories.

Labradorite is the most easily fusible of the feldspars; augite and magnetite are also easily fusible, so that basalt melts at a comparatively low temperature. Between 2000 and 2400 degrees of the Fahrenheit scale under ordinary atmospheric pressure it becomes fluid.

Basalt forms by far the larger part of the lava poured out by modern volcanoes, and occurs also in many dikes and in both extruded and intruded sheets. It is the most common of all the rocks with which the student of volcanoes has to deal.

Rhyolite (known also as *liparite* and *quartz-trachyte*) is composed of a fine-grained ground mass with crystals or crystalline kernels of sanidine (a glass-like feldspar), quartz, black mica, and hornblende, and a considerable variety of less abundant minerals scattered through it. While considerable diversity is exhibited in its texture, it may usually be recognized, or at least have its identity

suggested, by a certain flow-like arrangement of the minerals of which it is largely composed. In most instances it is apparent that the magma was fluid after the larger crystals had been developed in it and that a flowing motion caused the crystals to be arranged with their longer axes in parallel directions. This flow structure and the presence of prominent crystals of sanidine and quartz are the characteristic features that catch the eye in rough field examinations.

Rhyolite varies in color from black and dull gray to light pink and even pure white, and also exhibits all degrees of texture from light, porous pumice to compact glass. It is a common product of volcanic eruptions, although occurring in connection with but few still active volcanoes. It was poured out abundantly in comparatively recent geological times in the western part of the United States, and forms large portions of the mountains of Utah and Nevada. Its brilliant colors frequently give to the mountains of that arid and but scantily plant-clothed region, as rich and varied tints as are seen on the hills of New England in autumn.

Rocks composed of angular fragments of rhyolite, cemented so as to form a light, porous mass, termed *rhyolitic tuff*, occupies large areas in the Cordilleran region, and frequently surpasses the outcrops of massive rhyolite in brilliancy and variety of color. The Sunset Hills, Nevada, have been so named in reference to the varied color imparted to them by the tuff of which they are largely composed. Some of these tuff deposits are direct accumulations of lapilli, blown out of volcanoes in a state of violent eruption; while other deposits, frequently of great extent, are of the nature of mud

flows, the ejected fragments having been mixed with water so as to render the mass plastic, and allow it to flow even on gentle slopes.

The rhyolites are acid rocks, and among the most difficultly fusible of any of the volcanic series. Analyses of fifteen samples from widely separated localities, compiled by J. F. Kemp, show from 63.63 to 83.59 per cent of silica.

Trachyte. — This name was originally applied to a large group of rocks, characterized principally by their roughness and harshness to the touch, to which the name refers, but is now restricted to certain compact, porphyritic material, containing, as essential ingredients, sanidine with some other feldspar, and usually hornblende, biotite (black mica), magnetite, and other less common minerals, scattered through a glassy or finely crystalline ground mass.

Trachyte is distinguishable from rhyolite by the absence of quartz in conspicuous grains or crystals, and also by the absence of a flow structure. It is normally dark colored, but seldom has the black or greenish-black color of basalt, and differs from that rock also in containing sanidine, and being without grains or crystals of olivine. The trachytes are less acid than the rhyolites, the silica varying, ordinarily, from 57 to 66 per cent.

Andesite. — The rocks of this widely distributed group were first studied in the Andes, whence the name, and are described by E. H. Williams, as generally dark, and mostly fine-grained rocks, with a restricted amount of glassy base, but larger than in the trachytes. When examined under the microscope, they reveal a felt-like mass of minute crystals of plagioclase, hornblende, biotite,

and pyroxene, and may or may not contain quartz. In hornblende-andesite, crystals of plagioclase, hornblende in large black prisms and needles, and some augite may be distinguished by the unaided eye. In mica-andesite, biotite predominates over the hornblende.

The variety characterized by the presence of large-sized crystals of hornblende is common in the Cordilleras from Central America to Alaska, and in the prevalent rock met with in many of the great volcanic mountains of which Mt. Rainier and Mt. Shasta are representative.

The andesites contain from 56 to 67 per cent of silica, corresponding in this respect very closely with the trachytes.

Summary.—Under each of the typical and characteristic igneous rocks mentioned above, there are many subdivisions, and besides, there is a host of rock species, some of them common in many districts, that cannot be classed in the group to which attention has been directed. To attempt a more extended introduction to the study of rocks, however, is impracticable at this time; one reason being that the subject is so attractive that the reader would be in danger of losing sight of the main object of this book. Petrology is a highly specialized branch of geology, and one concerning which the general student cannot hope to obtain more than an unsatisfactory insight. Unfortunately, there is no ready way in which the species of fine-grained igneous rock can be certainly distinguished one from another, without the use of somewhat expensive apparatus. Thin sections have to be ground and examined with a microscope adapted to the purpose, before their mineralogical composition can be determined, and even then, owing to the great number

of varieties that occur and their gradations one into another, and the alterations that have taken place in numerous instances since the original cooling of the magma, no entirely satisfactory scheme of classification seems possible. The best that the beginner can do is to become acquainted with a few types of the most common occurrence. A few books have been mentioned in a preceding foot-note for the benefit of the student who may wish to learn more of the science of petrology.

CHAPTER II

GENERAL DISTRIBUTION OF THE ACTIVE AND RECENTLY EXTINCT VOLCANOES OF NORTH AMERICA

On the accompanying map, Plate 1, the distribution of the active and recently extinct volcanoes of the world is shown with as much accuracy as the scale of the map will allow. The most prominent fact brought out by a study of the geographical distribution of volcanoes is, that, with but few exceptions, they are situated on the borders of continents or on the ocean's floor, and are notably absent from the central portions of continental areas.

An inspection of the map just referred to, will show that the volcanoes of North America form a part of a great system of volcanic vents which may be said to surround the Pacific Ocean. This chain of fire, as it has been termed, beginning in Terra del Fuego, extends along the west border of South America, where its course is marked in the Andes by some of the loftiest igneous mountains in the world; it is narrow and well defined on the west border of Central America and far into Mexico, where still steaming craters, some of which are among the highest summits on the continent of North America, define its position. The volcanic belt broadens in the northern part of Mexico and the United States, but is unmarked by active craters. Again contracting and approaching close to the ocean's shore, and in several

instances marked by island volcanoes, the igneous belt follows the coast of British Columbia and Alaska, and extends westward throughout the length of the Aleutian islands. Still active craters in Alaska show the positions of earth fractures which unite the volcanic belt of the New World with the still more energetic volcanoes of Kamchatka, Corea, Japan, Formosa, the Philippine islands, New Guinea, New Hebrides, New Caledonia, and New Zealand. The length of this vast system of active volcanoes, from the southern end of South America about the northern Pacific to New Zealand, is about 30,000 miles. Within the embrace of the great curve, and rising from the deeply submerged floor of the Pacific, are many volcanic islands and still active craters.

A branch of the western arm of the volcanic system just referred to, embraces Java, Sumatra, etc. A corresponding offshoot of the eastern arm is marked by the volcanoes of the West Indies.

It is a matter of observation that the loftiest mountains of a continent face the largest ocean washing its shores. In a similar way it may be remembered from a study of the distribution of volcanoes, that the greatest volcanic belt in the world embraces the largest ocean. Whether this association indicates an essential or genetic connection between the height of mountains or the prevalence of volcanoes, and the extent of water bodies, remains to be shown.

The volcanic areas considered in this book form a part of the great Pacific belt, but include an exceptional portion of it, since from Central Mexico to southeastern Alaska there are no active vents. In this interval of some four thousand miles, however, there are many

recently extinct craters, as well as hot springs and geysers. It is in this break in the chain of steaming craters that the breadth of the volcanic belt is greatest. This coincidence is significant, as will be shown in advance.

An examination of the accompanying map of North America, Plate 4, in which the positions of most of the active and recently extinct volcanoes are indicated, will show that our studies are to be confined to the western portion of the continent, and for the most part, to the immediate border of the Pacific. No volcanoes sufficiently recent to be recognized by their topographic forms occur east of the sharply defined eastern border of the Cordilleran mountain series. The central and eastern portions of the United States, the central, eastern, and northern portions of Canada, and much of Alaska, excepting its immediate southern border, are without evidence of recent volcanic activity. No active or recently extinct volcanoes have been discovered in the Greenland region. Iceland, as is well known, is an active volcanic centre, but, as stated in the introduction, is not included in our present studies.

The most recent volcanic rocks in all of the vast region just referred to — east and north of the Cordilleran series and embracing five-sixths of North America — are, so far as known, confined to the Atlantic border and occur in the Newark system. Some accounts of these rocks have already been given in connection with other igneous intrusions. They were poured out in part as molten lavas during the Mesozoic era, or the middle age of the earth's geological history. Erosion has been so great since the volcanoes from which they came were in activity that scarcely a vestige of the cinder cones or of the mountains

they formed now remains. The preservation of such records as still exist is due to the fact that the volcanic rocks were buried beneath sedimentary deposits and, for a very long period, so depressed that they were below the ocean's level, and thus escaped removal by erosive agencies.

Still more remote in the earth's history, volcanic eruptions on a grand scale occurred in what is now the Appalachian region and in the Lake Superior basin. These ancient volcanoes are far beyond the horizon that limits the view presented in these pages. They illustrate the fact, however, that even in the remote past volcanoes were situated on continental borders. When the vents from which the rocks referred to were derived, were in activity, the continent had increased but little from its original Archæan nucleus, and the sea occupied the whole of what is now the Mississippi valley and the northward extension of the same interior basin to the Arctic regions.

The volcanic mountains with which we are now interested are nearly all of post-Tertiary age. Some of the lava flows of Idaho, Washington, etc., however, which we will have occasion to study, were poured out during the Tertiary and were buried beneath the sediments of great lakes, the date of which is recorded by the fossils they contain.

The portion of the Pacific volcanic belt along which I wish to take the reader, is only a score of miles wide in Central America, but broadens in the central part of Mexico somewhat abruptly to about 800 miles, and touches both the Gulf and Pacific coasts. A gradual increase in breadth occurs north of Mexico, and in the latitude of San Francisco and Denver it attains its maxi-

mum width — 1000 miles. When followed northward, it again contracts, and in Alaska is as narrow and sharply defined as in Central America. The narrow tapering southern extremity of this volcanic belt curves eastward; its similar northern extremity, which also contracts in breadth towards its extremity, curves westward.

It is a significant fact that it is in the narrow, curved extremities of this volcanic belt that volcanic eruptions have occurred most recently, and where all of the still active volcanoes of North America are situated. In the broader and less curved central portion, only extinct volcanoes occur.

Recent as has been the migration of civilized people into North America, they have witnessed volcanic outbreaks that are scarcely second to any that have occurred elsewhere on the earth during the same period. In some instances, volcanoes have been born and grown to be lofty mountains, with all the symmetry and grace of youth, since white men have occupied the land of their nativity. Neighboring mountains, built by similar forces in more distant times, exhibit the unmistakable marks of age. Their summits show but faint signs of the heat that once caused vast columns of steam to ascend above them. Others in the same series are cold and their craters overgrown with vegetation, or occupied by lakes, and even filled with snow and glacial ice. This succession from youth to old age is illustrated by an abundance of examples in the region we are to explore, and will enable us to sketch, in outline at least, the normal life history, as it may be termed, of a volcanic mountain.

The task we have undertaken is not only to learn the distribution of volcanoes in North America, and which

are active and which extinct, and the dates of their eruptions, the height and forms of the piles of ejected material of which they are composed, etc., but to study the changes that volcanic piles pass through, from the time subterranean forces lead to their birth and growth, to the time when the destructive agencies of the air remove such portions of them as are above sea level.

These studies of the changes in progress on the earth's surface lead directly to the consideration of still greater problems, — such as the origin of volcanoes, the relation of surface extrusions of molten rock to subterranean intrusions which form dikes, intruded sheets, cistern-like intrusions known as laccolites, and the origin of still greater dome-like uplifts due to an injection of plastic material beneath and termed subtuberant mountains. Beyond these problems, but intimately connected with them, is the consideration of the condition of the earth's interior, the reaction of the earth's crust on its still highly heated central portion as cooling progresses, the origin of continents, ocean basins, mountain ranges, etc. It is not to be hoped, from what is now known concerning the volcanoes of North America, that we will be able to answer satisfactorily all of the questions which suggest themselves in this connection, but we shall, I trust, be better able to understand the limiting conditions of these great problems and see them from various points of view. What is known concerning the volcanic history of the earth is certainly small in comparison with the portion still unknown. The hope of discovery should, therefore, stimulate the student at every step in this branch of nature study.

In the study of the volcanoes of North America, it is convenient to recognize three geographical divisions: 1st, a southern or Central American and Mexican region of active craters; 2d, a middle region of extinct or perhaps, in part, dormant volcanoes, extending from central Mexico through the western part of the United States and far into Canada; and 3d, a northern or Alaskan region of still steaming mountains. The general plan of our studies will conform to this arrangement.

CHAPTER III

VOLCANOES OF CENTRAL AMERICA

(The principal volcanoes of Central America are indicated on the map forming Plate 4.)

North and South America are connected by an isthmus the narrowest portion of which, barely twenty-two miles broad, is near its junction with the southern continent. It is there that the dividing line between the two continents of the New World is most naturally drawn. This division is the most natural one also in reference to the distribution of volcanoes, since in the Province of Panama there is a break in the great Pacific volcanic belt.

Popular descriptions of the volcanoes of Central America can be had in larger number, since volcanic mountains in most instances are conspicuous objects, and an eruption always commands attention, but to the special student a few typical examples are of more value than a multiplicity of general observations. With the exception of the admirable report of Dollfus and Mont-Serrat, and one or two less extensive accounts by trained observers, the literature bearing on the geography and geology of Central America is lacking in scientific value.

General Geography and Geology.—The information available concerning the geography and geology of Central America seems to show that the general features of that region resemble those of the Sierra Nevada. Throughout

Central America there is a tableland which presents a gentle slope to the northeast, but terminates abruptly on the southwest. Presumably this tableland is the surface of a tilted block of the earth's crust, or a series of such blocks, limited on the southwest by a narrow belt of intersecting and branching fractures. The main structural features, as just stated, resemble those of the Sierra Nevada, except that the upraised border of the tableland adjacent to the belt of fracture, faces westward instead of eastward. Along the belt of faulting adjacent to the west coast, there are scores of volcanic mountains which give to the scenery of Central America its culminating points and its chief attractions. The belt of fracture is sharply defined and is marked by hundreds of craters, solfataras, and hot springs. Evidently the fractures which admitted of the tilting of the eastward sloping tableland reached downward to regions where the rocks are intensely heated, and furnished passageways for the escape of molten rock. The region is humid and the surface rocks are water-charged. As the lava was forced upward from deep within the earth, it came in contact with water, and the steam generated escaped at the surface in many instances, with explosive violence. Nearly all of the volcanoes, so far as can be judged from the descriptions available, are of the Vesuvian type, and the elevations they have produced are mainly the result of the accumulation of projectiles. In numerous instances, however, streams of lava have flowed out, but as is the rule with most trachytic lava, the prevalent type in Central America and Mexico did not advance far or expand widely.

Distribution of the Volcanoes.—The belt of active and recently extinct volcanoes, seldom over fifty miles broad,

which skirts the Pacific coast of Central America, begins at the south in two prominent mountains which are reported to be extinct volcanoes, in the northern part of Panama. These peaks are known as Chiriqui and Rovalo; their elevations are 11,265 and 7021 feet, respectively. Of these two peaks, the first named is said to be the more typical example of a mountain built of extruded material, for the reason that it is a symmetrical cone with gracefully sloping sides. Associated with these two mountains is a third, known as Pico Blanco, 11,740 feet high, which has been reported by certain travellers to be also of volcanic origin, but is considered by other observers, and especially by W. M. Gabb,[1] as a remnant left by erosion of a great porphyritic dike.

This trio of mountains, clothed with luxuriant tropical vegetation, stands as a monument at the southern end of a vast series of cones, craters, and lava flows, which terminates some seven thousand miles to the northwestward, in the treeless, desolate, mist-covered Aleutian Islands. The striking contrasts in the present aspects of nature encountered as one traverses this volcanic belt from end to end, prepares one in a measure for the wonderful chapters of peace and war in the life history of our continent, revealed when its geology and geography are studied.

The volcanoes of Central America have not been thoroughly explored, but to bring together all of the scattered observations made by travellers and by the few trained observers who have visited the region, would lead to a great mass of details in which it would be difficult to trace a connection. I shall, therefore, present a list of the

[1] "Notes on Costa Rica Geography," in "American Journal of Science," Vol. 9, 3d Series, 1875, pp. 198–204.

best known volcanoes, accompanied by a few facts respecting their height and the dates of the latest eruptions, taken principally from Brigham's admirable narrative of his travels in Guatemala,[1] and follow this with a somewhat detailed account of a few of the most prominent and best known volcanoes. On the accompanying map, Plate 4, for which I am indebted largely to the book just referred to, the distribution of Central American volcanoes is shown.

In the following list of Central American volcanoes, so far as practicable, their order from southeast to northwest is indicated.

List of the Active and Recently Extinct Volcanoes of Central America

IN COLOMBIA

Name.	Present State.	Last Eruption.	Height.[2] Feet.
Chiriqui	?		11,265
Rovalo	?		7,021
Pico Blanco	Extinct		11,740

IN COSTA RICA

Name.	Present State.	Last Eruption.	Height.[2] Feet.
Chiripo	Extinct		
Turrialba	Extinct		12,523
Irazu, or Cartago	Active	1726	11,450
Barba	Extinct		
Los Votos, or Poas	Extinct		10,500
Tenorio	Extinct		
Miravalles	Extinct		5,500
Rincon de la Vieja	Quiescent		
Orosi	Quiescent		8,650

[1] W. T. Brigham, "Guatemala, the Land of the Quetzal," New York, 1887.

[2] The heights given cannot be considered, in most instances, as more than approximately correct.

IN NICARAGUA

Name.	Present State.	Last Eruption.	Height. Feet.
Madeira	Quiescent		5,000
Ometepe	Active	1883	5,050
Zapeton, or Zapatera	Extinct		
Mombacho	Extinct		5,250
Masaya	Active	1858	3,000
Nindiri	Quiescent		
Guanapepe	Extinct		
Momotombito	Extinct		
Momotombo	Active	1852	7,000
Axusco, or Asososco	Extinct		4,690
Las Pilas	Quiescent		4,000
Orota	Quiescent		
Telica	Active	1850	3,800
Santa Clara	Quiescent		4,700
El Viejo	Quiescent		5,562
Chonco	Quiescent		
Conseguina	Quiescent	1835	3,600

IN HONDURAS

Bay Islands	Extinct		1,000
Bonito	Quiescent		
Congrehoy Peak	Quiescent		8,040
Tigre	Extinct		2,632
Zacate Grande	Extinct		2,000

IN SAN SALVADOR

Conchagua	Quiescent		3,915
San Miguel	Active	1844	6,244
Chinameca	Quiescent		5,000
Usulutan	Extinct		
Tecapa	Extinct		
San Vicente	Quiescent	1643	7,600
Cojutepeque, or Ilopango	Active		3,400
San Salvador	Active		6,182
Izalco	Active	Constant	6,000
Santa Ana	Active		6,000
Apaneca	Extinct		5,826

IN GUATEMALA

Name.	Present State.	Last Eruption.	Height. Feet.
Ipala	Extinct		5,460
Monte Rico	Extinct		
Suchitan, or Santa Catarina	Extinct	1469?	
Mita	Extinct		5,000
Amayo	Extinct		
Chingo	Extinct		6,500
Moyuta	Extinct		
Tecuamburro	Extinct		
Cerro Redondo	Extinct		3,550
Pacaya (Pecul)	Quiescent	1775	8,390
Agua	Extinct		12,337
Fuego	Active	1880	12,075
Acatenango	Quiescent		13,563
Atitlan	Active	1852	9,870
San Pedro	Extinct		8,125
Santa Clara	Extinct		8,554
Zuñil	Extinct		
Cerro Quemado	Quiescent	1785	10,205
Santa Maria (Exancul)	Extinct		11,415
Tajamulco	Extinct		18,317?
Tacanà	Quiescent	1855	11,500

From this list let us select a few of the best known and most characteristic examples of volcanic phenomena for special study.

Young Volcanoes

At a few localities in various countries, as shown by historic records, fissures have opened in the earth, accompanied by earthquakes, and the escape of steam and molten rock, together with other phenomena characteristic of volcanoes, at localities where similar disturbances were previously unknown. In some of the instances referred to, the ejected material has accumulated about the opening

from which it was discharged, until a conspicuous hill, and even a mountain-like volcanic pile, has resulted. Not only have the births of volcanoes been observed, but also, in a few instances, their growth and action, until their energy has been expended and the span of their brief existence terminated.

One volcanic hill, named Monte Nuovo,[1] the history of which is well known, is situated in Italy between historic Lake Avernus and Baiæ Bay. This mountain, as it is termed, came into existence in 1538, soon attained a height of 440 feet, and then became extinct. A drive from Naples through a charming region will enable one to visit it and return in a single day.

Although Monte Nuovo is cited as the type of a young volcanic mountain in many books of geography and geology, and serves as an illustration of the manner in which molten material is extruded from the interior of the earth so as to make conspicuous surface changes, it is by no means as impressive an example of elevations built by volcanic forces within historic times, as three or four similar occurrences that have been witnessed in the New World. I refer to the young but still active volcano in San Salvador, known as Izalco, which came into existence in 1770; a nameless volcano in Nicaragua, the first eruption of which was witnessed by the American traveller, E. G. Squier, in 1850; an eruption in the centre of Lake Ilopango, San Salvador, in 1879; and the birth of Jorullo, in Mexico, in 1759. As these young volcanoes have features of general interest which supplement each

[1] An account of the origin and brief history of Monte Nuovo may be found in Lyell's "Principles of Geology," 11th edition, New York, 1874, Vol. I, pp. 607–619.

other, it is convenient to break the geographic order of our studies and consider them together.

Izalco. — The still active volcano known as Izalco, about thirty miles west of the city of San Salvador, is now approximately 3000 feet in height above the surrounding country, and rises about 5000 feet above sea level. Its prominence in the region in which it stands is due to the accumulation of lava, scoria, and lapilli about a centre of eruption, which first showed evidence of volcanic activity in 1770. The appearance of the cone of Izalco in 1894 is shown in Plate 5.

Accounts of the birth and growth of Izalco have been given by numerous writers, and especially by Humboldt, and within recent years, by Stephens, Squier, and Dollfus and Mont-Serrat.[1]

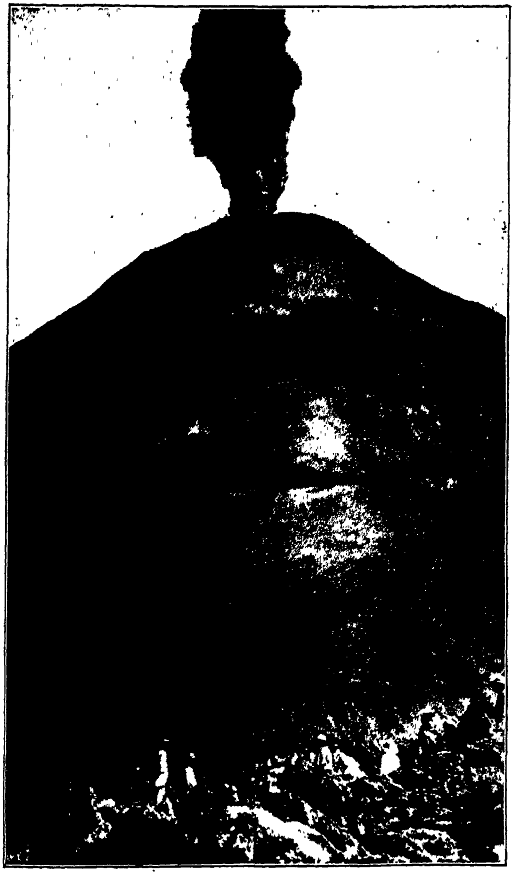
The account of this remarkable volcano given by Squier in his essay on the volcanoes of Central America, reads as follows:

"It arose from the plain in 1770, and covers what was then a fine cattle hacienda or estate. The occupants on this estate were alarmed by subterranean noises and shocks of earthquakes, about the end of 1769, which continued to increase in loudness and strength until the 23d of the February following, when the earth opened about half a mile from the dwellings on the estate, sending out

[1] A. von Humboldt, "Cosmos," New York, 1869, Vol. V, pp. 248, 249, 261. J. L. Stephens, "Incidents of Travel in Central America," [etc.], New York, 1841, Vol. I, pp. 325–330. There have been many editions of this work. E. G. Squier, "The States of Central America," New York, 1858, pp. 296, 297; "On the Volcanoes of Central America" [etc.], in American Association for the Advancement of Science, Proceedings, New Haven meeting, 1850, pp. 101–122. A. Dollfus et E. de Mont-Serrat, "Voyage géologique dans les républiques de Guatemala et de Salvador," Paris, 1868, pp. 376–406.

lava, accompanied by fire and smoke. The inhabitants fled; but the *vaqueros*, or herdsmen, who visited the estate daily, reported a constant increase in the smoke and flame, but that the ejection of lava was at times suspended, and vast quantities of ashes, cinders, and stones sent out instead, forming an increasing cone around the vent, or crater. This process was continued for a long period, but for many years the volcano has thrown out no lava. It has, however, remained in a state of constant eruption, the explosions occurring every sixteen minutes and a quarter, with a noise like the discharge of a park of artillery, accompanied by a dense smoke and a cloud of ashes and stones, which fall upon every side, and add to the height of the cone. It is now about 1500 or 2000 feet in height, and I am informed by an intelligent West Indian gentleman, Dr. Drivon, who has known it for the past twenty-five years [previous to 1850], that within that period it has increased about one-third. At some times the explosions are more violent than at others, and the ejected matter greater in amount; but it is said the discharges are always regular. With the wind in a favorable direction, an annoying and sometimes injurious quantity of fine ashes or powder is carried to the city of Sonsonate, twelve miles distant."

An extinct volcano near Izalco was ascended by Stephens in January, 1840, who gives in his well-known work of travel, already referred to, a graphic account of the appearance of the active crater as seen from above. From Sonsonate he heard the noise of the eruption of the volcano during the daytime and at night saw the light of the crater and the streams of lava rolling down its sides. Passing the town of Izalco, the travellers, quoting from



Izalco, San Salvador, 1894.

the narrative referred to, "soon came out on an open plain, and without a bush to obstruct the view, and saw on our left the whole volcano from its base to its top. It rose from near the foot of a mountain, to a height perhaps of 3000 feet, its sides brown and barren, and all around for miles the earth was covered with lava. Being in a state of eruption, it was impossible to ascend it, but behind it is a higher mountain, which commands a view of the burning crater. The whole volcano was in full sight, spouting into the air a column of black smoke and an immense body of stones, while the earth shook under our feet. . . . We came out suddenly upon an open point, higher than the top of the volcano, commanding a view of the interior of the crater, and so near it that we saw the huge stones as they separated in the air, and fell pattering around the sides of the volcano. In a few minutes our clothes were white with ashes, which fell around us with a noise like the sprinkling of rain.

"The crater had three orifices, one of which was inactive; another emitted constantly a rich blue smoke; and after a report, deep in the huge throat of the third appeared a light blue vapor, and then a mass of thick black smoke, whirling and struggling out in enormous wreaths, and rising in a dark majestic column, lighted for a moment by a sheet of flame; and when the smoke dispersed, the atmosphere was darkened by a shower of stones and ashes. This over, a moment of stillness followed, and then another report and eruption, and these continued regularly, at intervals, as one guide said, of exactly five minutes, and really he was not much out of the way. . . .

"The curé of Sonsonate, still in the vigor of life, told

me that he remembered when the ground on which this volcano stands had nothing to distinguish it from any other spot around. In 1798,[1] a small orifice was discovered puffing out small quantities of dust and pebbles. He was then living at Izalco, and, as a boy, was in the habit of going to look at it; and he had watched it and had marked its increase from year to year until it had grown into what it is now. . . ."

The next account we have of this young and still energetic volcano is by Dollfus and Mont-Serrat, who, finding it in a state of mild activity in 1866, climbed to its summit and made a survey and study of its environments. This is by far the most complete and scientific description of the mountain available, but, to avoid repetition, only a few notes of features of special interest will be taken from it.

On leaving Sonsonate, the travellers crossed a basaltic plain covered nearly everywhere with decomposed volcanic dust and lapilli, on which grew dense forests. At the immediate foot of the volcano, a black, desolate zone, in general five to six hundred metres broad, completely surrounded it. This lava field appears to have been a lake of molten rock without motion, and to have acquired a rough, scoriaceous surface on cooling and hardening. Near the base of the cone, the surrounding basalt has an upward slope toward the volcano, of two or three degrees, and exhibits also a more markedly scoriaceous surface. As one approaches still nearer the base of the volcano, the upward inclination increases to such an

[1] There is a discrepancy between this and other dates given for the beginning of the eruptions. What seem to be the most reliable records place it in 1770, as stated above.

extent as to make it seem as if the actual climb had begun.

Before the base of the volcano is reached, the lava gradually disappears beneath a covering of loose, angular rocks, and of smooth, rounded bombs with black, vitreous surfaces. This coarse material, varying in general from the size of one's hand to a cubic metre, came from the crater above and, rolling down its sides, formed a circle about its base.

The cone itself, at the date referred to, was 284 metres high above its immediate base on the north and 400 metres on the south side. It is composed of small, scoriaceous fragments (lapilli, volcanic gravel, and dust) ejected from the summit and deposited in layers which slope away from the crater rim in all directions. The cone is described as perfect in form and of graceful shape, — so regular and smooth, in fact, that it gives one the impression of having been turned in a lathe. The sides slope at angles of 35° and even of 40°. Such slopes are difficult of ascent, even when firm, but when composed of loose, incoherent lapilli, into which one sinks more than ankle deep at each step, the climb becomes exceedingly fatiguing. No pumice was seen, but the fragments of lava were frequently scoriaceous, light, and rough in texture, and varying in color from red through many shades of brown to black. Some of the black specimens resembled fragments of coke, having the same shining fissures and metallic lustre. The lapilli became finer toward the summit and were there coated with sulphurous and aluminous incrustations which, from a distance, resembled patches of snow.

On reaching the summit, the explorers found it to differ but little from its condition in 1840, when seen

by Stephens from a neighboring eminence. There were three craters, the central one being the largest and most active; and from it a great volume of vapor, darkened at times by dust shot upwards by explosions, was rolling out. This was a funnel-shaped depression eighty metres in diameter and about twenty-five metres deep. At its bottom there was a rectangular opening, like the mouth of a mining shaft, four by five metres in diameter, which led down to an unknown depth. From deep within this shaft came continually dull, rumbling sounds, as of steam escaping under high pressure. There were, besides, from time to time, quite violent detonations like distant thunder, occurring at intervals of fifteen minutes. Accompanying each of these disturbances, the vapor escaped with increased violence. Still other explosions, less pronounced but accompanied by a shaking of the ground, occurred at intervals of five minutes.

One of the most instructive of the phenomena observed was the escape of the heated vapors and gases at many points through the loose lapilli. These fumaroles could be divided in a general way into two classes, with reference to temperature and the nature of the emerging gases and vapors. The gases from the hotter orifices, ranging in temperature as high by estimate as 400°, were transparent or of a bluish color, and consisted principally of hydrochloric acid. The second series, with temperatures of 96° to 273°, emitted white vapors which consisted largely of steam, with hydrochloric, sulphuric, and other gases mingled with it. Steam seems to have been only a minor feature of the fumaroles. It is stated that nine-tenths of the exhalations consisted of hydrochloric acid.

Fifteen days after the visit of Dollfus and Mont-Serrat, Izalco was again in a state of violent eruption.

Birth of a Volcano in Lake Ilopango, Salvador. — Lake Ilopango, in the central part of Salvador, was the centre of a violent earthquake in 1879, which was followed by a rapid discharge of the water of the lake. In the course of fifty-four days the lake fell thirty-five feet, and discharged a volume of water through a surface channel, estimated at over 20,320 million cubic feet. During the earthquake the lake was greatly agitated, and immense volumes of steam rose from its central portion. On January 20, 1880, at eleven o'clock in the evening, a renewal of the disturbance of the water was noticed, and the next morning a pile of rocks was seen in the centre of the lake, from which rose a huge column of vapor. The eruption continued for more than a month; the island of rocks increased in size, and from it rose continuously a vapor column fully a thousand feet high. The waters of the lake became heated, and sulphurous vapors were emitted in such abundance as to be unpleasant when the wind blew from the east, in the city of San Salvador, about ten miles distant.

Previous to the disturbances just mentioned, Lake Ilopango was abundantly stocked with fishes, which were killed at an early stage of the outbreak. When the eruption terminated, the island that had been formed was found to have an area of about five acres, and a height of 160 feet. In its immediate vicinity soundings showed a depth of 100 fathoms of water.

The region all about Lake Ilopango is composed of volcanic rocks, and judging from the accounts available, the most authentic of which is a report by Edwin Rock-

stock to the government of Guatemala (San Salvador, 1880), it seems as if the lake occupies an ancient crater or perhaps a depression due to subterranean explosions, the outlet of which had been dammed by landslides. The partial drainage of the lake, as well as the formation of a volcanic island in its centre, are among the changes of greatest geographical interest that accompanied the eruption.

A Nameless Volcano in Nicaragua. — In the account of the volcanoes of Central America given by Squier, already referred to, there is an interesting description of the breaking forth of a new crater in the beautiful Plain of Leon to the southwest of Lake Nicaragua. This unique phenomenon is described as follows:

"In fact, I have been a personal witness of the origin of a new volcano, which, if it does not meet a premature extinguishment, bids fair to add another high cone to those which now stud the great Plain of Leon. . . . On the 11th and 12th days of April last [1850], rumbling sounds, resembling thunder, were heard in the city of Leon, situated in the centre of the plain I have described. They seemed to proceed from the direction of the volcanoes, and were supposed to come from the great volcano of Momotombo, which often emits noises and shows other symptoms of activity, besides sending out smoke. This volcano, however, on this occasion, exhibited no unusual indications. The sounds increased in loudness and frequency on the night of the 12th, and occasional tremors of the earth were felt on Leon. Early on the morning of Sunday, the 13th, an orifice opened near the base of the long-extinguished volcano of Las Pilas, about twenty miles distant from Leon. The throes of the earth at the

time of the outburst were very severe in the vicinity, resembling, from the accounts of the natives, a series of concussions. The precise point where the opening was made might be said to be in the plain; it was, however, somewhat elevated by the lava which had ages before flowed down from the volcano, and it was through this bed of lava that the eruption took place. No people reside within some miles of the spot; consequently I am not well informed concerning the earlier phenomena exhibited by the new volcano. It seems, however, that the outburst was attended with much flame, and that, at first, quantities of melted matter were ejected irregularly in every direction. Indeed, this was clearly the case, as was shown upon my visit to the spot some days thereafter. For a wide distance around were scattered large flakes resembling freshly cast iron. This irregular discharge continued only a few hours, and was followed by a current of lava, which flowed down the slope of the land toward the west, in the form of a high ridge, rising above the tops of the trees, and bearing down everything which opposed its progress. While this flow continued, which it did for the remainder of the day, the earth was quiet, excepting only a very slight tremor, which was not felt beyond a few miles. Upon the 14th, however, the lava stopped flowing, and an entirely new mode of action followed. A series of eruptions commenced, each lasting about three minutes, succeeded by a pause of equal duration. Each eruption was accompanied by concussions of the earth, too slight, however, to be felt at Leon, attended also by an outburst of flame a hundred feet or more in height. Showers of red-hot stones were also ejected with each eruption to the height of several hundred feet.

Most of these fell back in the mouth or crater, the rest falling outward, and gradually building up a cone around it. By the attrition of this process, the stones became more or less rounded, thus explaining a peculiarity in the volcanic stones already alluded to. These explosions continued uninterruptedly for seven days, and could be accurately observed from Leon in the night."

Observations made by Squier and his companion, Dr. J. W. Livingston, on visiting this young volcano, show that it presented on a small scale many of the phenomena to be seen when Vesuvius and other similar volcanoes are in eruption.

"In order to obtain a full view of the new volcano, we ascended a high, naked ridge of scoria, entirely overlooking it. From this point it presented the appearance of an immense kettle, upturned, with a hole knocked in the bottom, forming the crater. From this, upon one side, ran off the lava stream, yet fervent with heat, and sending off its tremulous radiations. The eruption had ceased that morning, but a volume of smoke was still emitted, which the strong northeast wind swept down in a trailing current along the tree-tops.

"The cone was patched over with yellow, crystallized sulphur, deposited from the hot vapors passing up among the loose stones. The trees all around were stripped of their limbs, leaves, and bark, and resembled so many giant skeletons. Tempted by the quietude of the volcano, and anxious to inspect it more closely, in spite of the entreaties of our guides, we descended from our position, and going to the windward scrambled over the intervening lava beds, through patches of thorny cactuses and agaves, toward the cone. On all sides we found the flakes

of melted matter which had been thrown out on the first day of the eruption, and which had moulded themselves over whatever they fell upon. We had no difficulty in reaching the base of the cone, the wind driving off the smoke and vapors to the leeward. It was perhaps a hundred and fifty or two hundred feet high, by two hundred yards in diameter at the base, and of great regularity of outline. It was made up entirely of stones, more or less rounded, and of every size from one pound up to five hundred. No sound was heard when we reached it, except a low, rumbling noise, accompanied by a slight tremulous motion. Anxious to examine it more closely, and to test the truth of the popular assertion that any marked disturbance near the volcanic vents is sure to bring on an eruption, we proceeded to ascend. Fearing we might find the stones too much heated near the summit, I prepared myself with two staffs, for support, and to save my hands; the doctor disdained such appliances, and started without them. The ascent was very laborious, the stones rolling away beneath our feet, and rattling down the sides. We, however, succeeded in almost reaching the summit, when Dr. Livingston, who was a little in advance, suddenly recoiled with an exclamation of pain, having all at once reached a layer of stones so hot as to blister his hands at the first touch. We paused for a moment, and I was looking to my footing when I was startled by an exclamation of terror from my companion, who gave simultaneously an almost superhuman leap down the side. At the same instant a strange roar almost deafened me; there seemed to be a whirl of the atmosphere, and a sinking of the mass upon which I was standing. Quick as thought I glanced upward; the heavens were black with stones,

and a thousand lightnings flashed among them. All this was in an instant, and in the same instant I too was dashing down the side, reaching the bottom at the same moment as my companion, and just in time to escape the stones, which fell in rattling torrents where we had stood a moment before. . . . The eruption lasted for nearly an hour, interspersed with lulls, like long breathings. The noise was that of innumerable blast furnaces in full operation, and the air was filled with projected and falling stones. . . ."

For several months after the eruption just described as stated by Squier, no eruption occurred, with the exception of one on May 27, which followed the falling of the *first considerable shower of rain.* The fact that an eruption followed the rain may have been a coincidence simply, but is suggestive, in connection with what is known concerning the part played by water in volcanic eruptions.

In order to bring the records of the young volcanoes of the North American continent into one group, we will borrow from a chapter in advance, which deals with the volcanic records of Mexico, an account of the birth of what is now an imposing mountain, known as Jorullo.

Jorullo, Mexico.—Jorullo, frequently cited as a volcanic mountain that was upraised in a single night, is situated about 170 miles westward of the city of Mexico. Its fame is due largely to the account of its origin and early history given by Humboldt,[1] who visited it fifty-six years after its birth.

In spite of the veneration we feel for the writings of

[1] A. von Humboldt, "Political Essay on the Kingdom of New Spain," translated by John Black, London, 1811, Vol. II, pp. 211–223. See also "Cosmos," translated by Otte and Paul, New York, 1869, Vol. V, pp. 293, 294, 297–304.

the immortal Humboldt, one is inclined, on reading his account of Jorullo, to question the authenticity of the information on which he bases his very graphic description. As stated by Humboldt, the account of the remarkable occurrence referred to, was sung in hexameter verses by the Jesuit Father Raphael Landivar, a native of Guatemala, and also recorded by the Abbé Clavigero, in an ancient history of his country ("Storia antica di Messico"). These writings, which it does not seem should be considered as possessing scientific accuracy, and the narratives of persons who witnessed the catastrophe, gathered over half a century after its occurrence, are the sources of the information on which Humboldt's frequently quoted description of the event are based. While the main features of the eruption given below may apparently be taken as approximately correct, many of the details are apparently exaggerated. The theory held by Humboldt, that volcanic craters are formed by the upheaval of the earth's crust, "crater of elevation," possibly influenced his interpretation of the reports of the eruption narrated to him. The account of the birth of Jorullo given by Humboldt in his essay on New Spain, but somewhat abbreviated, is as follows:

Jorullo, it is said, was formed in the night of September 29, 1759. Humboldt and Bonpland visited it and gained its summit in 1803. The plain on which Jorullo stands is elevated 750 to 800 metres above the sea and is surrounded by volcanic rocks. For some time previous to the date of the eruption just given, the middle of the plain was occupied by fields of sugar-cane and indigo. These fields belonged to the plantation of San Pedro de Jorullo. In the month of June, 1759, subterranean noises of an alarming nature were heard, accompanied by earthquakes, which

succeeded one another for fifty or sixty days. From the beginning of September, however, until the time of the eruption, tranquillity seemed restored, but in the night between September 28 and 29, the subterranean noises recommenced.

"The affrighted inhabitants fled to the mountains of Aguasarco. A tract of ground from three to four square miles[1] in extent, which goes by the name of *Malpays*, rose up in the shape of a bladder. The bounds of this convulsion are still distinguishable in the fractural strata. The *Malpays* [answering to the aa lava surfaces described on a previous page], near its edge, is only twelve metres above the old level of the plain called the *playas de Jorullo;* but the convexity of the ground thus thrown up increases progressively towards the centre to an elevation of 160 metres.

"Those who witnessed this catastrophe from the top of Aguasarco assert that flames were seen to issue forth for an extent of more than half a square league, that fragments of burning rocks were thrown up to prodigious heights, and that through a thick cloud of ashes, illuminated by the volcanic fire, the softened surface of the earth was seen to swell up like an agitated sea. The rivers of Cuitamba and San Pedro [elsewhere in the narrative termed *brooks*] precipitated themselves into the burning chasms. The decomposition of the water contributed to invigorate the flames, which were distinguishable at the city of Pascuaro [sixty statute miles distant], though situated on a very extensive tableland

[1] The translator remarks in a foot-note that "the French mile is, it is believed, nearly as 2.887 to 1, almost thrice the length of an English mile; but it is uncertain what mile the author uses here."

1400 metres elevated above the plains of *las playas de Jorullo*. Eruptions of mud, and especially of strata of clay enveloping balls of decomposed basalt in concentrical layers, appeared to indicate that subterranean water had no small share in producing this extraordinary revolution. Thousands of small cones, from two to three metres in height, called by the indigenes *ovens* (*hornitos*), issued forth from the *Malpays*. . . .

"In the midst of the ovens, six large masses, elevated from 400 to 500 metres each above the old level of the plain, sprung up from a chasm, of which the direction is from N.N.E. to the S.S.E. This is the phenomenon of the Montenovo of Naples, several times repeated in a range of volcanic hills. The most elevated of these enormous masses, which bears some resemblance to the *puys* de l'Auvergne, is the great Volcan de Jorullo. It is continually burning, and has thrown up from the north side an immense quantity of scorified and basaltic lavas containing fragments of primitive rocks. These great eruptions of the central volcano continued till the month of February, 1760. In the following years, they became gradually less frequent. . . . The roofs of the houses of Queretaro were then covered with ashes at a distance of more than forty-eight leagues in a straight line from the scene of the explosion. Although the subterraneous fire now appears far from violent, and the *Malpays* and the great volcano begin to be covered with vegetation, we nevertheless found the ambient air heated to such a degree by the action of the small ovens (*hornitos*), that the thermometer at a great distance from the surface and in the shade rose as high as 43° C." In the bottom of the crater, temperatures of 58° and 60° C. were

obtained. Fissures from which sulphurous vapors were escaping were found to have a temperature of 85° C.

There is much more in the narrative of Humboldt relating to the new volcano, but I doubt its value when considered in the light of modern science. Although the main facts secured are seemingly correct, the student of volcanic phenomena will, I think, take exceptions to many of the details reported by priests and Indians, and also to the interpretations of these reports by Humboldt.

The four young volcanoes described in the last few pages are of great interest as showing the nature of the phenomena that attend the formation of new volcanic vents. If, however, we consider a volcano as the surface manifestation of an opening or conduit, leading down to a central region of intense heat in the lower portion of the earth's crust, it seems doubtful if we should consider the examples cited as new volcanoes in the strict meaning of the term. In each case, the outbreak of steam, lava, etc., has been in a volcanic region and in the immediate vicinity of dormant or extinct craters. It would seem rather that old passageways have become closed and the imprisoned steam generated by water coming in contact with highly heated rocks, or the effects of renewed pressure on the reservoirs deep below the surface, has led to the opening of new vents along a line of ancient fracture.

Older Volcanoes

From the numerous and, for the most part, popular accounts of the volcanoes of Central America that have been published, it is impossible to select sufficient well-

authenticated data to enable one to compile an adequate history of the igneous mountains of that region.

The facts in hand show that about thirty volcanoes have been more or less active within historic times. These are indicated on the list already presented. Hundreds of craters that have ceased to emit molten lava, scoria, lapilli, etc., still discharge steam and sulphurous vapors, and may, therefore, be classed as solfataras. Throughout the volcanic belt, hot springs are numerous, which no doubt, in most instances, owe their high temperature to the heat of volcanic rocks below the surface, but these have received little scientific attention. In this region, also, earthquakes have been of frequent occurrence and, in some instances, intimately associated with volcanic outbursts.

Among the rocks in the volcanic region mentioned by travellers or described by the few geologists who have studied them, basalt is of limited occurrence. The mountains are composed principally of trachytic rocks, and the country over large areas is deeply covered with lapilli, pumice, dust, etc., which record the energy of explosive volcanic eruptions. It is the decay of these fragmental products especially, under the influence of tropical rains and a high temperature, that gives to much of Central America its wonderfully rich soils.

Instead of attempting to assemble all the available data relating to the older volcanoes of Central America, I shall select a few of the most typical examples of volcanic eruptions and of volcanic mountains, not alone for their geographical interest, but as illustrations of the life histories of volcanoes in general. The examples chosen are Conseguina, Fuego, and Agua.

Conseguina.—Of all the volcanoes on the North American continent, none have attracted a greater share of attention than Conseguina. It is placed first among the volcanoes here especially considered, having "by merit been raised to that bad eminence," on account of its fearful eruption in 1835. Previous to the explosion of Krakatoa in 1883, Conseguina, together with Sumbawa on the

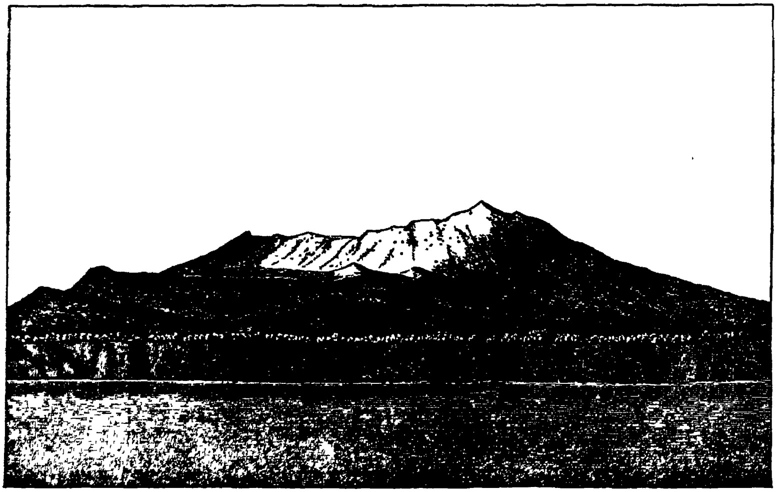


FIG. 6. Sketch of Conseguina. (Dollfus and Mont-Serrat.)

island of Sumatra served as the best example of volcanic explosion on record.

Conseguina is situated on the Pacific coast of Nicaragua, and forms the principal elevation of a peninsula which projects from the mainland towards the northwest and partially shuts off the Bay of Fonseca from the sea. The volcano is now extinct or dormant. From a distance it presents the appearance of a truncated cone, with an extreme elevation above the sea of a little less than four thousand feet. When more closely examined the low

mountain is found to contain a comparatively large crater-like depression in its summit.

Of the appearance of Conseguina previous to its now historic eruption in 1835, there seems to be no authentic record. At that time the summit of the mountain, which had been formed by material ejected during previous eruptions of a milder character, was literally blown away, and the rocks composing it reduced to fragments and distributed far and wide over the adjacent sea and land. By extending upward the sides of the truncated cone now remaining, an approximate restoration of the form of the original mountain may be made, which indicates that its height was in the neighborhood of 8000 or 10,000 feet. This estimate, however, would be approximately correct only in case the mountain had been formed by comparatively mild explosive eruptions. It may have been truncated by violent explosions, previous to the one of which we have a record.

The appearance of Conseguina as seen from the sea is shown in the accompanying sketch, copied from Dollfus and Mont-Serrat.[1] The crater within the truncated cone has a diameter of four miles and a depth below the highest point of its rim of three hundred feet.

Of the many accounts of the eruption of Conseguina that have been published, the most graphic as well as the most accurate, so far as I can judge, is one compiled by Squier,[2] about fifteen years after the occurrence. This account reads as follows:

[1] A. Dollfus et E. de Mont-Serrat, "Voyage géologique dans les républiques de Guatemala et de Salvador," Paris, 1868.

[2] E. G. Squier, "On the Volcanoes of Central America," American Association for the Advancement of Science, Proceedings, New Haven meeting, 1850, pp. 107–109.

"On the morning of the 20th of January in that year [1835], several loud explosions were heard for a radius of a hundred leagues around this volcano, followed by the rising of an inky black cloud above it, through which darted tongues of flame resembling lightning. This cloud gradually spread outward, obscuring the sun, and shedding over everything a yellow, sickly light, and at the same time depositing a fine sand, which rendered respiration difficult and painful. This continued for two days, the obscuration becoming more and more dense, the sand falling more thickly, and the explosions becoming louder and more frequent. On the third day, the explosions attained their maximum, and the darkness became intense. Sand continued to fall, and the people deserted their houses, fearing the roofs might yield beneath the weight. This sand fell several inches deep at Leon, more than one hundred miles distant. It fell in Jamaica, Vera Cruz, and Santa Fé de Bogota, over an area of 1500 miles in diameter. The noise of the explosions was heard nearly as far, and the Superintendent of Belize, eight hundred miles distant, mustered his troops, under the impression that there was a naval action off the harbor. All nature seemed overawed; the birds deserted the air, and the wild beasts their fastnesses, crouching, terror-stricken and harmless, in the dwellings of men. The people for a hundred leagues grouped, dumb with horror, amidst the thick darkness, bearing crosses on their shoulders and stones on their heads, in penitential abasement and dismay. Many believed the day of doom had come, and crowded to the tottering churches, where, in the pauses of the explosions, the voices of the priests were heard in solemn invocation to Heaven. The brightest lights were

invisible at the distance of a few feet; and to heighten the terror of the scene, occasional lightnings traversed the darkness, shedding a lurid glare over the earth. This continued for forty-three hours, and then gradually passed away.

"For some leagues around the volcano, the sand and ashes had fallen to a depth of several feet. Of course, the operations of the volcano could only be known by the results. A crater had been opened, several miles in circumference [about twelve miles, according to Dollfus and Mont-Serrat], from which had flowed vast quantities of lava into the sea on one hand, and the Gulf of Fonseca on the other. The verdant sides of the mountain were now rough, burned, and seamed, and covered with disrupted rocks and fields of lava. The quantity of matter ejected was incredible in amount. I am informed by the captain of a vessel which passed along the coast a few days thereafter, that the sea for fifty leagues was covered with floating masses of pumice, and that he sailed for a whole day through it without being able to distinguish, except here and there, an open space of water.

"The appearance of this mountain is now desolate beyond description. Not a trace of life appears upon its parched sides. Here and there are openings emitting steam, small jets of smoke, and sulphurous vapors, and in some places the ground is swampy from thermal springs. It is said that the discharge of ashes, sand, and lava was followed by a flow of water, and the story seems corroborated by the particular smoothness of some parts of the slope."

The terror inspired in the minds of the people inhabiting the region about Conseguina calls to mind the graphic

picture of the destruction of Pompeii during an eruption of Vesuvius, given by Bulwer. The eruptions in each instance were of a similar character, the summit of a mountain in each case being blown to fragments.

The explosion as witnessed at the town of La Union on the northwest shore of the Bay of Fonseca, about forty miles distant from Conseguina, has been described by Lieutenant Colonel C. Manuel Romero,[1] commandant of the post, from whose account the following has been compiled:

The dawn of the day on which the eruption began (January 20, 1835) was serene, but at eight o'clock a dense black cloud was seen rising toward the southeast, preceded by a rumbling noise. The cloud continued to ascend until about ten o'clock, when it covered the sun and then began to spread toward the north and south; it continued to spread until it covered the whole firmament, and at about eleven o'clock enveloped everything in the greatest darkness. The darkness was so intense that the nearest objects were imperceptible. During this spreading of the cloud it was rent by lightning flashes, accompanied by thunder. At four in the afternoon, the earth began to quake, and continued in a perpetual undulation, which gradually increased in force. Next came a shower of what is stated to have been "phosphoric sand," which lasted until eight in the evening, when a fine, heavy powder like flour began falling. Lightning and thunder continued the whole night, and the following day (January 21) at eight minutes past three in the afternoon, an earthquake shock of such violence occurred that men were thrown down.

[1] Reprinted from "Boletin oficial del Estado de Guatemala," 1835, by Dollfus and Mont-Serrat, p. 334. A translation by Colonel Juan Galindo may be found in the American Journal of Science, Vol. 28, 1835, pp. 332–334.

The effects of the appalling scene on men and beasts were also noted. The darkness lasted for forty-three hours. On the 22d, it was less dark, although the sun was still invisible, and towards morning on the 23d. tremendously loud thunder claps were heard in succession, like the firing of the heaviest of artillery. This fresh occurrence was followed by an increase in the dust shower.

On the 25th, 26th, and 27th, there were frequent, although not violent, earthquake shocks. The showers of dust lasted until the 27th. Galindo mentions other eruptions that occurred at the same time with the outburst of Conseguina, five of which continued for eight days. In conclusion he says: "The volcanic energy seems to have operated on an extensive scale, and to have had vent in a great number of places. The country from Bogota, about latitude 4° 30′ N., longitude 74° 14′ W., throughout the whole isthmus, certainly as far as Belize [more than 1000 miles from the centre of disturbance] was convulsed, or affected by the concussions."

Following the great explosion just described came fearful earthquakes along the Andes. The most disastrous of these was on February 20th, but they continued at the rate of three or four a day up to March 6th, and less frequently to March 17th. During one of these earthquakes, the city of Conception, Chile, with a population of 25,000, was destroyed, only a single house remaining standing.

After the eruption of Conseguina, brilliant sunsets and sunrises, due to the quantity of fine particles blown high in the air and drifted by the wind to distant regions, were observed at widely separated localities.

The great eruption of Conseguina, 1835, just described, presented in many ways the phenomena that accompanied

the explosion of Krakatoa in 1883. The latter eruption was more carefully studied and a far better report made concerning it than in the case of the former. A better conception of what took place at the explosion of Conseguina can be gathered from reading the account of the eruption of Krakatoa given on a previous page, in connection with the reports just cited, than can be had from the imperfect and unscientific accounts which are alone available concerning the occurrence.

As will be seen when the theories advanced to explain volcanic eruptions are considered, the violent explosions that shook Central America at the time the summit of Conseguina was blown away, were caused by an escape of steam augmented perhaps by the ignition of gases. A large volume of water probably gained access to the liquid lava that rose in the conduit of the volcano, and the steam and gases generated blew the liquid lava and the enclosing rocks to fragments and showered them over the surrounding region.

Volcan del Fuego.—Since the Spanish conquest about fifty volcanic eruptions have been chronicled in Central America. Of these, twenty are accredited to Fuego. This unusually energetic volcano was in full activity at the time of the Spanish invasion, but became less and less demonstrative during the sixteenth and seventeenth centuries, and for many years has been in the solfataric stage. The recent quiescence is to be regarded with suspicion, however, since, like many other volcanoes of Central America, Fuego is of the Vesuvian type. A period of rest may mean that the lava in the upper part of its conduit is slowly cooling and hardening, so as to confine the steam generated beneath, which will finally gain such

energy as to again open a passage to the surface. When this occurs, the history of Vesuvius in 79, or of Conseguina in 1835, may be repeated.

Fuego, Agua, Acatenango the highest summit in Central America, and a number of smaller volcanoes, form a secondary group trending approximately north and south, and nearly at right angles to the main volcanic belt. All of the craters in this group, except Fuego, are extinct or have long since passed to the solfataric stage.

The volcano of Fuego and its higher neighbor, Acatenango, called also Pico Mayor and Padre del Volcan, are united up to an elevation of 3000 metres, but above that elevation rise as independent cones. Fuego is a perfectly regular cone of lapilli with surface slopes of 28° to 32°, on all sides, except the north, where a prominent shoulder 330 metres below its summit, termed la Meseta, gives it an exceptional profile. This table-like projection is a remnant of a vast truncated cone, the summit of which was blown away in prehistoric times, and bears a similar relation to the modern cone towering above it, that Somma does to Vesuvius.

Regarding the past activity of Fuego, Dollfus and Mont-Serrat[1] state that it had probably been in activity for a long time previous to the Spanish invasion of Guatemala, as the natives at that time held it in dread. During the following centuries its eruptions were frequent and terrible. It occupied a leading place among the many active volcanoes which at the time referred to were covering Central America with lava and storms of cinders and lapilli.

[1] A. Dollfus et E. de Mont-Serrat, "Voyage géologique dans les républiques de Guatemala et de Salvador," Paris, 1888.

Among the more violent eruptions are cited those of 1526, 1541, the 27th of December, 1581, when the quantity of lapilli and dust projected into the atmosphere was so great that the sun was completely obscured, and lamps were lighted at midday at La Antigua, fifteen kilometres distant. During 1582, 1585, and 1586 there were eruptions almost every month; the most terrible being on December 23, 1586. Memorable eruptions occurred also in 1614, 1623, 1686, 1705, 1706. On August 27 and 28, 1717, explosions covered the surrounding country with cinders; accompanying this eruption violent subterranean detonations are recorded. Other eruptions occurred in 1732, 1739, 1829, and 1855. On January 9, 1856, cinders were shot into the air, with such violence that they fell at Tocoy, 150 kilometres to the northward; it is remarked that these cinders contained ten per cent of magnetic iron. The volcano was again in eruption on February 17, 1857. Finally, on August 17, 1860, there was a small eruption, but since that date to 1866 (and I believe to the present time, 1896) this remarkable volcano has been quiet, although there is always a cloud of steam above its summit.

The numerous eruptions recorded were nearly all of the explosive type; the material ejected being usually scoria, cinders, lapilli, and blackish or violet colored volcanic sand. No great effusions of lava are mentioned, but a few small flows have occurred from fissures near the base of the cone. No molten lava is known to have been erupted from the summit.

Dollfus and Mont-Serrat ascended Fuego in May, 1866. After traversing the dense tropical forests on the lower slopes of the mountain, the region of pines was reached

at an elevation of about 3000 metres. A little below la Maseta the pines gave place to grass-covered slopes, but this is not the true "timber line." The forests cease because the lapilli of which the ground is composed has not decayed sufficiently to form a soil. On neighboring peaks the forest reaches an elevation of 4000 metres, and even the highest summits when soil is present are grass covered.

At the summit there is an irregular crater fifty metres wide and twenty-five metres deep, floored with lapilli, in the walls and bottom of which there are several fumaroles. This crater has evidently been inactive for some time, but, at a little lower level to the southwest, there is a gigantic cavity, partially defacing its rim, from which immense volumes of vapor pour out. This active crater is almost circular, with a diameter of 300 or 400 metres, and a depth of 600 metres. The bottom is of scoria, although it must have been an open conduit at the time of the eruption of 1860. The walls of the crater are nearly vertical, and highest on the northern side adjacent to the small summit crater.

The rim of the great crater, in common with nearly the entire surface of the mountain, is composed of black, brown, and red scoria, and lapilli, the larger fragments being about the size of one's fist. The outer slopes of the cone near the top, as well as the inner edges of the crater, are covered over large areas with white and yellow incrustations, deposited from the exhalations of numerous fumaroles. Both within the craters and on the adjacent outer slopes there are many localities where steam and gases escape, and join the vapors rising from within the main crater. The temperature of these fumaroles ranges from 79° to 110°. As previously noted at Izalco, the

fumaroles with low temperatures give out steam mingled with small amounts of hydrochloric, sulphuric, and carbonic acids, etc., while from those with higher temperatures a decrease in the volume of steam, accompanied by an increase of gases, was noted.

In conclusion, Dollfus and Mont-Serrat state that in spite of the important rôle that Fuego has already played, it will not soon be stricken from the list of the active volcanoes of Central America.

Volcan de Agua. — It is instructive to turn from the still active craters of Central America, and note the condition of those which have long been extinct. Perhaps the most interesting example of this nature is furnished by Volcan de Agua, situated in Guatemala, and a near neighbor of the extremely active Volcan del Fuego, of which a short account has just been given, and of the ancient and now much weathered volcanic peak, known as Pacaya.

The account of Agua here presented is taken almost wholly from the great work of Dollfus and Mont-Serrat, already referred to. These authors state that the scene which the traveller beholds from the summit of Pacaya is one of the most imposing imaginable. One sees in a single glance, grouped as in a picture, the grand outlines of Fuego, and in the foreground the harmonious, gently curving lines leading to the tapering summit of Agua. The beauty of the scene is due in a great measure to a slight irregularity which, without affecting the symmetry of the grouping of the peaks, brings Agua one or two kilometres north of the general direction of the other elevations, and so permits the eye to sweep over a great expanse without interruption.

Considered by itself Agua is one of the most remarkable

volcanic mountains in Central America. Its beauty is due not only to its considerable height and the luxuriousness of the forests about its base and clothing its lower slopes, but, in a great measure, to its isolation. It rises as a single cone to an elevation of 3753 metres above the sea. Its immediate base covers an area of several hundred square kilometres. To the north its lower slope merges with the spurs of a mountain known as Santa Maria, but to the south its visual height is almost 3500 metres. To the east and west it is separated from Pacaya and Fuego by valleys which it overtops by more than 2000 metres. Its isolation is thus complete. Having been extinct for a long time, its surface is broken by stream channels, but these irregularities are slight, and disappear when the mountain is viewed from a distance.

Vegetation has completely covered the great cone, and, thanks to its isolation, the normal distribution of plant life according to climatic belts is clearly marked. A series of well-defined plant zones can be seen surrounding the cone, which play an important part in beautifying it, and in imparting to it a harmonious variety of colors. Cultivated fields surround the base of the mountain, and extend up its sides to an elevation of 2580 metres. In ascending, one passes in upward succession productive fields of sugar-cane, coffee, and maize; then comes a splendid forest of various kinds of trees, including a number of tropical species. This forest continues to a height of 3027 metres, and then gives place abruptly to vast open spaces with sparsely growing pines, between which are luxuriant shrubs and flowers of species unknown in the lower region. The extreme summit and the floor of the crater which there exists, are grass covered.

The name of this charming mountain, Volcan de Agua, or water volcano, has led some persons to suppose that it is a volcano which erupts water; while others state that snow on its sides is sometimes melted by the heat from within, and descends in floods into the neighboring valleys. We are assured by Dollfus and Mont-Serrat, however, that neither of these explanations is correct. The origin of the name is this: at the time of the Spanish invasion, the crater at the summit of the mountain contained a lake, which was supplied by rain. In 1541, as the result of an earthquake, the wall of the crater on the northeastern side gave way, and an immense volume of water poured down the mountain side, carrying with it earth, rocks, and trees that obstructed its course, and overwhelmed a village which had been built by the Spaniards on the site where to-day stands the town of Ciudad Vieja.

The present condition of the mountain confirms this account, which has been derived from historical records. The crater presents all the characteristics of a former lake basin, and upon the side of the mountain an immense ravine can be clearly seen, departing from a place where the rim of the crater is broken, and extending in the direction of Ciudad Vieja.

The soil of the valleys near the base of Agua is described in the book we are citing, as being composed of layers of white pumice, yellowish cinders, black lapilli, and violet sands. No traces of lava flows were found. On the lower slope of the cone, where the ground has an inclination of from 28° to 30°, the fertile soil contains pumice and scoria, with a good proportion of yellow clay. At an elevation of 2664 metres, in an opening cleared in the dense forest, the soil was found to consist of a thick

layer of decayed volcanic sands and black lapilli in small fragments. The vast abundance of material such as is ejected during explosive eruptions, and the absence of lava flows, as well as the character of the crater walls, which are also of fragmental products, show that Agua, during its days of activity, was a volcano of the explosive type. Its perfection of form is no doubt due to its having been built by the accumulation of projectiles shot into the air, and falling about their place of egress. The eruptions were probably never sufficiently violent to blow away the summit of the cone, and, so far as known, no breaks in its sides led to the formation of dikes. Its grace and symmetry indicate that it was built up by long-continued but comparatively mild, explosive eruptions.

CHAPTER IV

VOLCANOES OF MEXICO

The distribution of the better known volcanoes of Mexico is shown on Plate 4.

HUMBOLDT states that the only volcanoes in Mexico that have been active within historic times are Tuxtla, Popocatepetl, Jorullo, and Colima, but this list has been somewhat extended since he wrote. The geology of Mexico is still but imperfectly known. Travellers report many craters and mountains besides those just mentioned, that are of recent date, and also extensive lava fields and vast deposits of lapilli and volcanic dust, which are the last additions made to the soil over broad regions.

The narrow belt of fractures and faults, with their accompanying volcanic phenomena, which is such a pronounced feature in the geology and geography of Central America, is continued into Mexico with a marked increase in breadth. In south-central Mexico the volcanic belt broadens until it touches both the Gulf and Pacific coasts. Accompanying this increase in width is a decrease in the number of active craters, and a diminution in their intensity. All of the still active volcanoes are confined to the region south of latitude 22°; that is, they are situated south of an east and west line, crossing the Republic about 200 miles north of the city of Mexico.

The best accounts of the physical geography of Mexico that have come under my notice, are in the well-known

writings of Humboldt, and in the recently published volume entitled "North America," by Réclus.[1] Descriptions of Mexican volcanoes, in most instances of a popular character, have been given by numerous travellers and by Spanish priests. In a few instances definite and reliable observations have been made by members of scientific expeditions; among these, the ones that have been found of most assistance are those published by the Geological Survey of Mexico. From this varied store of information, I have selected such facts as will assist the student in grasping the leading characteristics of volcanoes in general, and, at the same time, furnish information concerning the physical geography and geology of Mexico.

Orizaba. — This remarkably regular and beautiful symmetrical mountain is situated in the eastern part of Mexico, and a little south of a straight line joining the city of Mexico and Vera Cruz. It is about seventy-five miles west of Vera Cruz, and in sight from that city. Orizaba derives its present name from the city of Orizaba, near which it rises, and is known also by its ancient Aztec name, Citlal-tepetl, or Star Mountain. Its elevation is approximately 18,200 feet. For a time it was considered the highest summit in North America, but is now known to be surpassed in elevation by Mt. Logan (19,500), situated in northwestern Canada, near the Alaskan boundary. Triangulations made by Ferrer in 1796 placed the height of Orizaba at 17,879 feet. Humboldt, by similar methods, but, as he states, under unfavorable conditions, found it to be 17,375 feet.[2] Recent measurements by

[1] Élisée Réclus, "The Earth and its Inhabitants: North America." Edited by A. H. Keane, New York, 1891, Vol. II.

[2] "Cosmos," New York, 1869, Vol. V, p. 239.

means of an aneroid barometer, gave an elevation of 18.205 feet.[1]

Orizaba rises from a forested region and reaches the lower limit of perpetual snow, but no glaciers have been reported to occur about its summit. The upper limit of forest growth, or the "timber line," is at an elevation of about 12,000 feet. Above that elevation the rocks are bare until the snow that usually covers the summit is reached.

At the summit, there are three craters, separated one from another by ridges of lapilli. The shapes of these depressions show that but little erosion has taken place since the eruptions that gave them their forms. The last observed eruption is stated to have occurred near the middle of the eighteenth century. The igneous energy that built the mountain is now extinct or dormant, and the craters are normally occupied by snow. Like Mt. Etna, and many other isolated volcanic mountains, Orizaba is surrounded by eruptive rocks, and its flanks studded with numerous cinder cones and craters of small size. Much of the lava surrounding it came from its own eruptions, and some of the secondary cones are evidently parasitic;

[1] The elevations of four of the higher volcanic mountains of Mexico were measured by Professor Angelo Heilprin in 1889 (Philadelphia Acad. Nat. Sci., Proc., 1890, pp. 251–265) by means of an *aneroid barometer*, and the following results obtained:

Elevation of	Orizaba,	18,205	feet	above	the	sea.
"	Popocatepetl,	17,523	"	"	"	"
"	Ixtaccihuatl,	16,960	"	"	"	"
"	Nevado de Toluca,	14,954	"	"	"	"

These results differ considerably in each instance from previous measurements, and, on account of the method employed, cannot, in the opinion of men well qualified to judge of such matters, be considered as more than approximately accurate. The possible error in each case may be as great as five hundred feet.

that is, they owe their origin to the escape of steam from the lava flows on which they are located, and do not indicate the presence of vents connected with conduits leading to deeply seated regions of heated rocks. Other crater and lava flows apparently owe their origin to the opening of fissures in the sides of the mountain, which gave egress to lava and steam derived from the main conduit of the volcano.

The summit of Orizaba was first reached by Reynolds and Maynard, who were connected with the army of the United States which invaded Mexico in 1848. Since that time several ascents have been made. One of the latest of these was by an expedition sent out by the Academy of Natural Science of Philadelphia, in 1889, in charge of Heilprin. From an account of this ascent the following notes have been taken:[1]

The starting-point for the ascent was San Andres, a railroad town about midway between the city of Mexico and Vera Cruz. San Andres has an elevation of about 8200 feet. About the town there is a desert of sand, scantily clothed with aloes, cactuses, and yuccas, with here and there a cherry, oak, and an apple tree. To the eastward of San Andres, and barely twenty-five miles distant, rises the truncated cone of Orizaba, and its twin neighbor Sierra Negra; to the west and south are numerous volcanic cones, with elevations varying from 300 to 500 feet above the arid lands surrounding their bases.

At an elevation of about 1000 feet above San Andres, the exploring party left the dreary, open country with its

[1] Angelo Heilprin, "Among the World's Highest Mountains: an Ascent of Orizaba, Mexico." In "Around the World" (a magazine published in Philadelphia), Vol. 1, 1894, pp. 21–26, 49–53, with illustrations.

desert vegetation, and entered a region of pines. The species of pine that is most abundant in the lower portion of the forest belt is the long-leaved *Pinus Montezuma* (var. *macrophylla*). This tree is found, seemingly, on the slopes of all the giant volcanoes of the Republic, associated more or less with a closely related form, the *Pinus pseudostrobus*, and with *Pinus Teocote*. The Montezuma pine grows also in the neighborhood of the town of Orizaba, at an elevation of 4500 feet; and on the southwest slope of the volcano of Jorullo, where it descends to 4000 feet. It flourishes side by side with the palmetto in the transition zone which unites the vegetation of the lowlands with that of the uplands. This pine is of stately presence. Its shaft is frequently a hundred feet or more in height, and grows in open ranks with little or no undergrowth. On the lower slopes of Orizaba, Heilprin says: "We wander through a dense park, into which vistas of rare beauty open up at almost every point. Here the distant valley unfolds itself a boundless panorama; there the majestic cone of Orizaba, white with the frost of ages, towers far into the region of eternal cloudland."

At an elevation of between 10,000 and 10,500 feet, a belt of spruce trees (*Abies religiosa*) was entered, but, on its lower margin, oaks had already begun to appear. The pine, however, still continues to be the dominant form of arborescent vegetation. Flowering plants were not specially numerous, the most noticeable being a lupine and several species of senecio. At an elevation of about 12,000 feet, the forests terminate, and a broad, open, grass-covered belt encircles the cone below the lower limit of perennial snow.

The divide between the Sierra Negra and the peak of

Orizaba offers a splendid view of each of these volcanoes. The former barely reaches the line of perpetual snow, and shows well the effects of long-continued atmospheric erosion; the latter, white with frost, retains the contours which were impressed upon it at about the time of the last eruption. At various places on the flanks of Orizaba dark buttresses of rock stand out in vertical masses, showing where eruptions of greater or less magnitude have marked epochs in the history of the mountain. Huge outwellings of lava seam the slopes in radiating lines, but they belong in great part to a period of volcanic activity when the centre of eruption was located some little distance from the site of the present crater.

At an elevation of 14,500 to 15,000 feet, the zone of grasses terminates with an irregular edge. With the grasses are a few flowering plants.

The last traces of terrestrial animal life occur at about 15,000 feet, where, Heilprin says, "we picked up a solitary lizard from one of the sun-warmed boulders. There were no insects, at least we failed to find any traces of their existence, at this altitude. But birds were still observed and heard above us; we thought we recognized the tit and the chickadee, and possibly a species of wren. There was no question as to the raven, whose 'caw' was heard far o'ertop of us, or the sparrow-hawk. At about one o'clock we reached the ice-cap [elevation 15,500 feet], which is here split by a ridge of rock and boulders entering far into its limits. . . . The snow field, or more correctly ice field, was of inconsiderable development, at no point when seen by us attaining a greater thickness than about 5–7 feet. Its surface was everywhere cut up into sharp pinnacles (séracs) two or three feet in height, which,

while offering safe lodgement to the feet, rendered progress exceedingly irksome. There was no soft snow, and the feet made but little impression on the crusty surface of the ice."

In ascending Orizaba when the sky is clear, magnificent views are obtained of the great tableland of central Mexico on the west, and of the shore of the Gulf on the east. As described by Heilprin, at an elevation of 15,000 feet, the lofty summits of Popocatepetl and Ixtaccihuatl came into view, through the haze, although one hundred miles or more distant, and were boldly outlined against the western sky. As in most high mountains, however, the truly picturesque scenes are to be observed from the lower slopes. Views from lofty summits resemble maps rather than pictures.

In comparison with many other mountains of similar height, Orizaba is easy of ascent. The height of the timber line, 12,000 feet, leaves but 6000 feet above the highest camp fire. The elevation above the point at which a camp can be established, furnishes a rough measure, in many instances, of the difficulties to be overcome in mountain climbing. Heilprin states that from bottom to top, there are no precipices to climb, no impending ledges to crawl around or over, and no glaciers to cross. In these respects Orizaba agrees with Popocatepetl, while it differs greatly from Ixtaccihuatl. "The slope from the plateau base to the summit is pleasingly gentle and uniform, and the traveller who is bent upon making the attack requires merely a staff, proper foot gear, and a good constitution."

Popocatepetl. — The second mountain in Mexico in reference to altitude is Popocatepetl, or the Smoking

Mountain. Triangulations made by Humboldt[1] in 1804 gave 17,728 feet, while aneroid measurements by Heilprin[2] in 1889, already referred to, gave 17,523 feet as the height of the summit. More recent measurements by the Mexican Geological Survey[3] place the elevation at 17,876 feet.

For many years Popocatepetl was thought to be the highest mountain in North America, but it is now known to be surpassed by at least three other peaks on this continent.

Popocatepetl is a conical peak with a depression or crater in its summit. On the rim of the crater there are two prominent crags, connected by a narrow ridge; the higher of these is known as Pico Mayor, and the other has been named Espinazo del Diablo. The bottom of the crater is 1656 feet below the summit of the highest spire on its rim; the surface diameter of the great bowl is about 2000 feet. From fissures in the bottom of the crater steam still escapes, but the heat is not sufficient to melt the winter's snow, which reaches a depth of eight or ten feet, and covers the outer slopes of the mountain down to an elevation on the north side, of 14,268 feet. A thousand feet below the snow line is the upper limit of vegetation. All of the lower slopes are clothed with forests, which in places attain a tropical luxuriance. The melting snows supply a small lake in the crater, and the water percolating through the porous lava-sand feeds copious thermal springs about the base of the mountain.

[1] "Cosmos," New York, 1869, Vol. V, p. 427.

[2] Philadelphia Acad. Nat. Sci., Proc., 1890, pp. 251–265.

[3] J. G. Aguilera and E. Ordoñez, "Expedición científica al Popocatepetl," Mexico, 1895.

This percolation of meteoric water through the rocks, illustrates one of the important processes by which a volcanic mountain parts with its heat.

Popocatepetl stands on the eastern edge of the great central plateau of Mexico. On one side it looks down on the capital of the Republic, and on the other descends into the tropical lowlands bordering the central plateau. The visual height, as seen from the city of Mexico, is 10,000 feet; and from the lowland to the eastward, about 17,000 feet. Seen from the basal plains, it sweeps up in one grand curve to nearly its full height, — a colossus of three and a quarter miles in elevation, white with everlasting frost on its summit, and bathed in the green of palms, bananas, oranges, and mangoes at its base. Evergreen oaks and pines encircle its middle height, and above them, before the ice itself is reached, occur broad areas of loose sand into which the lavas have been changed by weathering. Soft wreaths of sulphurous vapor may at times be seen curling over the crest of the summit crater, — gentle reminders that the days of volcanic activity are not yet necessarily over.

The ascent of Popocatepetl, as stated by Heilprin,[1] is neither a difficult or dangerous task. One or more ascents are probably made each year. Horses can mount without much difficulty to an elevation of 13,000 or 14,000 feet, and might be urged still higher. The view from the summit is almost incomparably grand, reaching on clear days from the Gulf of Mexico almost to the Pacific. In three directions the view is unbroken except by the limitations of vision; on the fourth (to the north)

[1] "Around the World" (a magazine published in Philadelphia), Vol. 1, 1894, p. 13, with a fine illustration.

it embraces a colossus of nearly the same height as the great "Smoking Mountain" itself, the famous Ixtaccihuatl, or "White Woman."

Although rising fully 3000 feet above the snow line, its snowy covering is inconsiderable; rarely does it measure more than three to six feet in depth. Nothing worthy to be considered as a glacier is found on the mountain.

Many ascents of Popocatepetl have been made not only by travellers, but by *volcaneros*, who gather sulphur from the crater. It has been estimated that about fifty tons of sulphur are obtained annually, the supply being renewed by condensation from escaping vapors. The crude methods heretofore employed to gather and transport the sulphur, are to be supplanted, it is said, by more enlightened processes, under the management of a syndicate.

In 1895, a short account was published of a scientific expedition to Popocatepetl, by the Mexican Geological Survey,[1] which adds much to the geological history of the mountain previously recorded.

The crater is described by the explorers just mentioned, who spent twenty-eight hours in examining it, as elliptical in outline, with sloping walls, and with axes measuring 612 and 400 metres, respectively. Owing to marked irregularities in the height of the rim of the crater, its depth may be variously stated. Its bottom is 505 metres below the summit of the highest pinnacle, Pico Mayor, and 205 metres below the lowest point on its rim.

"Popocatepetl is a cone formed by an accumulation of many successive currents of lava, covered with fragmen-

[1] J. G. Aguilera and Ezequiel Ordoñez, "Expedición científica al Popocatepetl," pp. 1–48, Pl. 1–6. The notes here quoted are from an abstract of the report printed in the "American Geologist," Vol. XVII, 1896, pp. 330, 331.

tary materials, stones, sand, ashes, etc., and corresponds to those volcanoes called by some geologists 'stratified cones.' The lower or older of these currents shows a rock structure more granular and less lustrous than that of the later ones. Polarized light also reveals a crystalline development in the former, which is not found in the more glassy and amorphous structure of the latter. From these and other facts, the authors deduce the conclusion that the history of the volcano has been marked by three stages, which they denominate *período cinerógeno*, *período brechógeno*, and *período lávico*. The earliest, the lava period, was the longest; during the second, the ejecta consisted largely of pumice, mixed at times with volcanic bombs—blocks of andesite of the same nature as the lava; the third has supplied showers of ashes, which overlie the older products and have been much eroded by winds and rain. These periods the authors correlate with the Pliocene, Pleistocene, and Recent. Some of the earlier andesite lava flows are buried beneath beds containing remains of the horse and elephant, while a stream of very liquid basalt from the neighboring peak of Xitli overlies not only deposits containing vertebrate fossils, but even human remains.

"Three kinds of eruptive matter are defined,—labradorite-basalt, hypersthene-andesite, and trachyte, of which the first is the oldest, and is found in the lowest currents; but the grand cone is mostly composed of the second, which varies in structure from holocrystalline to vitreous, while the little summits consist of the third kind of ejecta.

"In the various facts given, the authors see a record of the original great energy and gradual decay of the vol-

canic action which has now almost ceased, nothing but smoke and vapor issuing from the cone."

As stated by Réclus,[1] there are reasons for believing that the first person who ascended Popocatepetl was the Spanish captain, Diego de Ordaz, who was with Cortes in 1519, but authorities are cited which render it uncertain that he gained the summit.

Ixtaccihuatl. — Rising to the north of Popocatepetl, and, like its greater neighbor, in full view from the city of Mexico, stands Ixtaccihuatl, or the "White Woman," as the mountain was named by the Aztecs. The summits of these two giant peaks are barely ten miles apart. The description of an ascent of Popocatepetl, already cited, would apply in all its general features to its near neighbor, and need not be repeated.

The height of Ixtaccihuatl is given by Heilprin as 16,960 feet, but other measurements, which so far as can be judged are equally trustworthy, make it some 500 feet less. Some writers have asserted that this grand peak is not of volcanic origin, but fail to give reasons for considering it to have a different history than the neighboring volcanoes, which it closely resembles. Its conical form and the fact that it is largely composed of trachytic rocks, seem to show that it owes its prominence to volcanic agencies. It is evidently older than Popocatepetl, and has undoubtedly been decreased in height by erosion. There is no crater at the summit, and no evidence of lingering volcanic heat. The summit is snow-capped even in summer. The original crater may reasonably be supposed to have been filled by the

[1] Élisée Réclus, "The Earth and its Inhabitants: North America," New York, 1891, Vol. II, p. 27.

washing in of its sides, and the summit angle of the peak blunted by the same process.

Xinantecatl. — About forty miles southwest of the city of Mexico near the city of Toluca, rises a symmetrical volcanic pile with gentle slopes, to a height of about 15,000 feet, which is known as Nevado de Toluca, or the "Snow of Toluca." Its Aztec name is Xinantecatl, or the "Naked Lord."

The summit of Xinantecatl, as seen from the south, barely reaches the lower limit of perpetual snow, but its northern side is white, even in September and October, the months when the melting and evaporation of the snow is most advanced. In the summit of the peak there are two craters, which are now flooded and form lakes of fresh water, with a combined area of about eighty acres. The larger lake is reputed to be thirty feet deep and inhabited by fish of a peculiar species.

Xinantecatl furnishes an example of an extinct or dormant volcano, and serves to connect in one series certain older volcanoes like Ixtaccihuatl, which have been exposed to storms and frosts for such a length of time that their craters have disappeared, with volcanic mountains of recent date like Popocatepetl, which not only still retain their summit craters but are yet giving out steam and heated gases.

Tuxtla. — Volcan de Tuxtla, situated on the coast of the Gulf of Mexico, about eighty miles southeast of Vera Cruz, is reported to be 4950 feet high. In 1664, it erupted molten lava, but again became quiescent, until March, 1793, when one of the grandest volcanic outbreaks of modern times occurred. This eruption was of the explosive type, and rivalled in energy the catastrophe that

blew away the summit of Conseguina in 1835. Scoria, lapilli, and dust were blown into the air with such violence that they rose thousands of feet and were carried by the wind 150 miles towards the northwest, and about the same distance to the southwest. The roofs of houses in Vera Cruz, Perote, and Oaxaca were covered with lapilli and dust. The noise of the explosion sounded like heavy guns and was heard distinctly at Perote, about 150 miles to the northwest.

Since the great eruption just referred to, less violent discharges from the same vent have taken place. The small height of Tuxtla is due to the blowing away of the summit of the mountain during a great explosion in 1793, and illustrates the fact that young and energetic volcanic mountains are not necessarily lofty. Mild explosions, if long continued, tend to build up symmetrical peaks with gracefully curving slopes, but when the energy of the explosions increases, the summits of the volcanoes in which they occur are frequently blown away, and the fragments distributed far and wide over the adjacent region. Low mountains with abnormally large craters are the results of such catastrophes. In fact, when the explosions are excessively violent, nothing to suggest a mountain remains, but great pits in the earth without elevated rims sometimes result. This is forcibly illustrated in the case of Krakatoa in 1883, already described, when not only was a mountain blown away, but a depression 3000 feet deep left to mark its site. It does not follow, however, that all large craters, "calderas," and "crater-rings," are to be accounted for in this manner, as the drawing off of the liquid lava from a crater and the tumbling in of its walls may produce similar results.

Cofre de Perote.—About thirty miles north of the peak of Orizaba, there stands a mountain about 13,552 feet high, with a quadrangular summit. When seen from the neighboring portion of the Gulf of Mexico, the summit of the peak has a resemblance to a coffer, or sarcophagus, which has suggested its modern name. To the Aztecs it was known as Nauhcampa-tepetl, or "Four-ridged Mountain." Surrounding the base of the mountain, and evidently originating from it, is a deposit of lava and pumice, which gives the country an uneven surface, and has gained for it the name *malapais* or "bad country." This term is used in several parts of Mexico for rugged lava flows and has been adopted somewhat generally by American geologists as a technical name for lava sheets with rough surfaces composed of angular blocks of rock, similar to the aa surfaces of the lava streams of Hawaii. The Cofre was ascended by Humboldt in 1804 and its altitude and position determined. Nothing of the nature of a crater was found at the summit, but the rock of which the mountain is largely composed is termed a *dioritic trachyte*. Streams of hardened lava radiate from the mountain, and record the energy of its ancient discharges. Humboldt found only isolated patches of snow about the summit in the month of February, which reached down to a limit of 12,500 feet, and about 700 or 800 feet below the upper limit of forest growth. The top is bare of snow in late summer and autumn.

The Cofre is evidently a volcanic cone that has passed its youth and has yielded, to a marked degree, to the attacks of erosive agencies. To Humboldt it appeared to furnish an example of a mountain upraised by forces acting from beneath and to be a "crater of elevation."

This hypothesis to account for the origin of volcanic mountains has for the most part been abandoned, for the reason that it is now well known that volcanoes build up elevations by extruding lava and by blowing out projectiles which accumulate about the opening from which they came, but not by pronounced upheaval of the earth's crust. Humboldt's account of the Cofre is of interest as illustrating his hypothesis of the origin of volcanic mountains by upheaval, as well as for the observed facts it contains. He says[1]: "In ascending the mountain I saw no trace of the falling in of a crater, or of eruptive orifices on its declivities; no masses of scoriæ, and no obsidians, pearlites, or pumice-stones belonging to it. The blackish-gray rock is very uniformly composed of much hornblende and a species of feldspar, which is not glassy feldspar (sanidine) but oligoclase; this would show the entire rock, which is not porous, to be a dioritic trachytê. I describe the impressions which I experienced. If the terrible, black lava fields — malapais — (upon which I have here purposely dwelt in order to counteract the too one-sided consideration of exertions of volcanic force from the interior) did not flow from the Cofre de Perote itself at a lateral opening, still the upheaval of this isolated mountain, 13,553 feet in height, may have caused the formation of the Loma de Toblas [the flat-topped summit rock from which the mountain derives its name]. During such an upheaval, longitudinal fissures and networks of fissures may be produced far and wide by folding of the soil, and from these molten masses may have poured directly, sometimes as dense masses, and sometimes as scoriaceous lava, without any formation of true

[1] "Cosmos," New York, 1869, Vol. V, pp. 308, 309.

mountain platforms (open cones or craters of elevation). Do we not seek in vain in the great mountains of basalt and porphyritic slate for central points (crater mountains), or lower circumvallated, circular chasms, to which their common production might be ascribed?"

This is only a portion of Humboldt's discussion of the origin of volcanic mountains, presented in connection with his account of the Cofre, but nowhere does he seem to recognize the changes that a mountain passes through when subjected to the destructive influence of the atmosphere. If one has in mind the fact that a mountain with an open crater at the summit may, by erosion, be transformed into a more obtuse cone, or bell-shaped pile, by having the crater walls removed, many of the difficulties encountered by geologists half a century or more ago disappear; and a sequence of topographic forms due to volcanic extrusion, and another equally interesting series resulting from decay, disintegration, and erosion, come into view.

Colima. — On the west coast of Mexico, and bearing much the same relation to the seaport of Manzanillo that Tuxtla does to Vera Cruz, is a volcano known as Colima. As stated by Humboldt, Colima is about 5500 feet high, and at the time of his visit to Mexico, frequently ejected lapilli, accompanied by vapor. It presents a fine sight from the town of Colima, from which it takes its name. In winter it is frequently whitened with snow.

In recent years, Colima has been more active than during the earlier portion of the present century. Eruptions occurred in 1869, 1872, and 1873. In 1885 lapilli was thrown out and carried by the wind 280 miles to the

northeast. Lava was also discharged during these eruptions, but nearly always from lateral openings, the "sons of Colima" as they are locally termed, and formed small craters on the adjacent plain.[1]

Ceboruco, or Ahuacatlan. — This mountain, with an elevation of about 7140 feet, rises near the Pacific coast, a few miles south of San Blas, and is the most northerly of the recently active volcanoes of Mexico. In 1870, it became violently active, and since then has never ceased to emit steam. The volcano is the centre of a group of craters. Of these there are two of large size and about 1000 feet deep each, one of which still emits steam, but the other is to all appearance extinct.[1]

Volcanoes of Northern Mexico. — To enumerate the remainder of the active or recently extinct volcanoes of Mexico, concerning which general information is available, would necessitate much repetition, and probably lead to confusion instead of serving to illustrate the laws which govern volcanic action.

North of the region in south-central Mexico, which is studded with great volcanic mountains and is a direct continuation, but marked by a conspicuous increase in breadth, of the Central American volcanic chain, there are broad fields of rugged lava with a considerable number of craters in various stages of decay and dilapidation. This broader portion of the volcanic belt already referred to, without active craters, belongs geographically with the still broader region of former volcanic activity in the United States and extending for an undetermined distance into Canada, and does not claim special attention at this time.

[1] Réclus, "North America," Vol. II, 1891, p. 24.

Volcanoes of Lower California. — In the portion of Mexico known as Lower California, volcanic mountains and lava fields also occur; but in the absence of scientific exploration little need be said concerning them. From various sources I learn that Lower California is traversed from north to south by an elevated region, much of which is composed of volcanic rocks. The highest summits are at the north, where Mt. Calamahue, or Santa Catalina, rises to a height of approximately 10,000 feet and reaches the lower limit of perpetual snow.

Midway down the Peninsula, and overlooking the Gulf on the east, stands a group of volcanic peaks known as the Tres Virgenes, which are reported to be from 6600 to 7250 feet high. An eruption occurred in this group in 1857, and since then steam has been emitted, sometimes in large volumes.

CHAPTER V

VOLCANOES OF THE UNITED STATES

(The distribution of the principal volcanoes of the United States is shown in Plate 4.)

A GENERAL account of the distribution of the volcanoes of the United States has already been given. It will be remembered that they occur in the Cordilleran region to the west of the meridian of Denver.

In the Cordilleran region the surface rocks are largely of igneous origin. Nearly every mountain range has an igneous core or has lava sheets or craters associated with it. In several instances entire mountain ranges are composed of rocks that were once molten. The rocks referred to are of all ages, from the Archæan to recent times. It is only to those of volcanic origin, however, and of such a late date that but moderate changes have resulted from erosive agencies, that attention is here invited. The lava flows in numerous instances are still rough and bare of vegetation, and the craters as perfect in outline as when still steaming.

It does not seem desirable at this time to attempt a minute description of the hundreds of lava flows and craters within the United States, even if the investigation of this branch of the ancient history of our country was sufficiently advanced to make such a course possible.

My plan, therefore, will be to select a few typical examples of volcanic mountains and of lava sheets, for presentation.

San Francisco Mountain, Arizona, and Adjacent Craters. —The highest and most prominent group of mountain peaks in the southwestern portion of the United States is in northern Arizona, about twelve miles north of the town of Flagstaff, and known as the San Francisco mountains. (Plate 6, Fig. A.) The Atlantic and Pacific railroad passes through Flagstaff, and passengers by that route usually have many fine views of the neighboring mountains, through the open forest of pines that clothes the plateau on which they stand, and extends far up their sides. The highest peak rises 12,562 feet above the sea, and 5700 feet above the general level of the surrounding tableland.

The San Francisco group, according to G. K. Gilbert,[1] includes a series of large peaks of trachyte, the products of massive eruptions, and a multitude of small scoria cones, associated with broad and, in part, thick sheets of basaltic lava.

The larger cones are of comparatively ancient date, possibly Tertiary, and are much wasted by erosion. The summits are sharp, their sides deeply scored with ravines, and nothing to represent a crater remains.

Much more recent than the main peaks are the smaller craters of black basalt adjoining them, especially to the eastward. Many of these craters are as perfect as when first formed. The streams of black, scoriaceous lava that escaped from some of them and spread out on the sur-

[1] "Geographical and Geological Explorations and Surveys West of the 100th Meridian," Vol. III, "Geology," 1875, pp. 129, 130.

rounding plain, are so fresh in appearance that to an observer looking down on them from the sides of the main elevations, they seem scarcely to have cooled from their original molten condition. The number of these recent vents is stated by Gilbert to be some hundreds. As many as one hundred are marked by cinder cones. Sixty-five with craters partially or wholly preserved may be counted. Some of the craters are intensely black, with large areas of dark red where oxidation has taken place, and are entirely free of vegetation; on others, desert shrubs have ascended the slopes, and conceal in part the ruggedness of the angular and broken lava and scoria. At least one of the craters contains a lake. A view over this desert of lava studded with craters several hundred feet high, some of which have great gaps in their rims through which floods of molten lava once escaped, calls vividly to mind the illustrations published by Scrope,[1] of the now classic volcanoes of central France.

Mt. Taylor,[2] New Mexico. — The western part of New Mexico owes much of its characteristic scenery to the presence of high tablelands, separated by regions of deep erosion. One of these tablelands, or *mesas*, is covered with lava flows, and sustains a prominent volcanic pile named Mt. Taylor. The mountain has an elevation of 11,390 feet above the sea. The mesa from which it rises is forty-seven miles long from northeast to south-

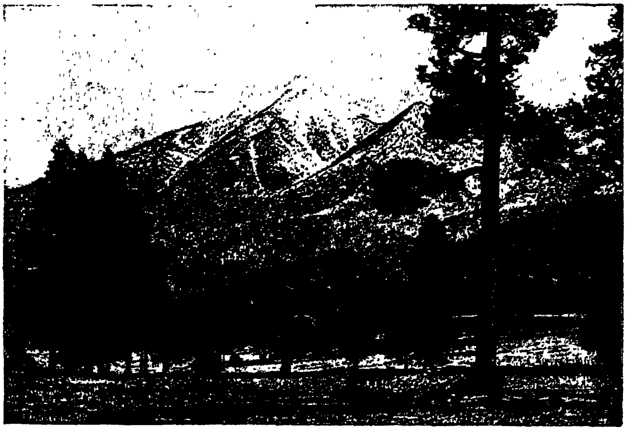
[1] G. P. Scrope, "The Geology and Extinct Volcanoes of Central France," London, 1858, Pl. 3, 5.

[2] The most readily available source of information concerning Mt. Taylor and the adjacent region, is "Mt. Taylor and the Zuñi Plateau," by C. E. Dutton, in the 6th Annual Report of the U. S. Geological Survey, 1884–85, pp. 105–198.

west, and twenty-three miles broad. Its margins are irregular and deeply indented. It has a general elevation of 8200 feet, and rises in general 2000 feet above the more thoroughly eroded country with which it is surrounded. The mesa is a relic left by erosion, and furnishes a measure of a portion of the general lowering of the surface of the adjacent country, that has taken place owing to the action of rain, rivers, and other denuding agencies. The reason why the rocks forming the basement layer of the mesa have escaped destruction and caused it to become a prominent topographical feature as the adjacent region was lowered, is because of a surface layer of lava about 300 feet thick, which resisted the attack of atmospheric agencies much more effectually than the sedimentary strata surrounding it. The Mt. Taylor mesa and neighboring elevated areas of the same general nature, are literally roofed with lava, which has shed off the rain, and protected the strata beneath.

Mt. Taylor is composed almost entirely of lava, which rose through a single opening and built up a prominent cone with a large crater in the summit. The primitive form is now greatly altered by erosion. It stands as a ruin, in which one sees with difficulty the outlines that gave it form and expression during its days of maturity. The geographer and geologist in the Mt. Taylor region, however, find less of interest in the mountain itself than in its surroundings.

If we stand, says Dutton, on the eastern brink of the Mt. Taylor mesa, the view in the valley of the Puerco to the eastward is in some respects extraordinary. The edge of the mesa suddenly descends by a succession of ledges and slopes, nearly 2000 feet into the rugged and



San Francisco Peak. Agassiz Peak.

FIG. A. San Francisco Mountain, Arizona, from the southwest. (C. E. Dutton.)

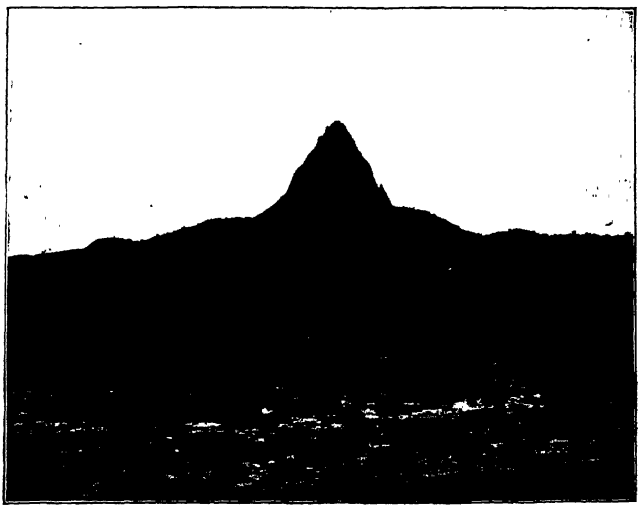


FIG. B. Volcanic neck near Mt. Taylor, New Mexico. (Photograph by U. S. Geological Survey.)

highly diversified valley-plain below. The country beneath is a medley of low cliffs or bluffs, showing the browns and pale yellows of the Cretaceous sandstones and shales. Out of this confused patchwork of bright colors rise several objects of remarkable aspect. They are apparently inaccessible eyries of black rock that rise from 800 to 1500 feet above the general level of the valley. The black piles, that by contrast of form and color make such a marked innovation in the scenery of the arid valley, are the "necks" of ancient volcanoes. To understand their history, we must restore in fancy the rocks which have been carried away to form the valley, and possibly much more. Upward through the horizontally bedded rocks, openings were formed in some manner, but how is not fully known, and through these openings, lava rose to the surface and formed cones similar to the scores of cinder cones still to be seen on the Mt. Taylor mesa, and about San Francisco peak. How widely the lava spread out in sheets can only be conjectured. When the eruptions ceased, the lava slowly cooled and solidified in the chimneys through which it came. Plugs of dense rock, many times beautifully columned on account of shrinkage on cooling, were formed, which were far more resistant to erosion than the stratified beds through which they rose. Then came a long period of erosion, in the course of which many hundreds of feet of sedimentary rock, and all the lava sheets and cinder cones which may have rested upon them, were swept away from areas which aggregate thousands of square miles. The necks of resistant volcanic rock in the ancient chimneys resisted waste and decay much more effectually than the softer beds of shale and sandstone with which they were surrounded, and became

prominent landmarks as the general surface was lowered. The leading outlines in this slow process of differential erosion are simple, well understood, and similar to what has occurred over wide regions of the earth's surface; but the results produced are unusually striking, owing to the bold relief of the isolated neck, the contrast of their sombre precipices with the brightly colored desert-valley about them, and the general absence of vegetation. The time required for the unearthing of the formerly buried buttes is vast, as measured in years. The date at which the ancient volcanoes were active is placed by geologists in the Tertiary period of the earth's history.

A view of one of the volcanic necks described above is given on Plate 6, Fig. B, and will serve to show the general features of scores of similar isolated piles, more or less completely buried by the products of their own disintegration and decay, that add variety and interest to the desolate region about Mt. Taylor.

The completeness of the evidence by which the history just outlined is sustained, is shown by the fact that the volcanic necks most remote from the edge of the mesa have been completely exhumed and disengaged from the stratified beds that formerly surrounded them, while those nearer the mesa still have large remnants of the enclosing strata around their bases and mounting far up their sides. Nearer still to the border of the mesa, the amount and height of the enclosing beds increase, so that only the summits of the necks protrude. In the wall of the mesa itself, there are instances in which the volcanoes have been cut in two and one-half removed, so as to expose not only the summit of the neck of hardened lava, but a section of the cinder cone that was built above it. The

one or two hundred cinder cones on the Mt. Taylor mesa illustrate the character of the surface which has been removed in the valley of the Puerco, in order to reveal the volcanic necks. The volcanic cones on the surface of the mesa are in various stages of decay, but some of them still retain their craters. Two of them are between 800 and 1000 feet high, and four or five others are only a little smaller. The distribution of these vents upon the mesa is very irregular. In some places they are thickly clustered together; in others they are separated by intervals of three or four miles.

Much detailed information concerning the volcanic necks in the region about Mt. Taylor is given by Dutton in the attractive report from which the above descriptions are taken, and the student who has become interested in their history should consult the volume to which reference has been made.

In the valley of Rio San José, to the south and west of the Mt. Taylor plateau, there are lava flows with extremely rugged surfaces, some of which are so recent that time has made no appreciable impression on them. These lava flows are to be seen from the trains on the Atlantic and Pacific railroad, near Laguna, and farther westward from McCarty to Blue Water. Portions of this route furnish typical examples of what the Mexicans term *malpais*, that is, the rough surfaces of lava that have been broken and the blocks piled together in confused heaps as the still liquid portion below continued to flow. The glossy black and exceedingly rugged surfaces of some of the lava coulées along the San José are of this type. In other places the corrugated surfaces of slowly moving sheets which cooled without being broken into blocks,

furnish unmistakable evidence of the former liquid condition of the rock.

Dutton discovered that the vent from which came the lava in the valley of Rio San José, is a low crater named Tintero (the inkstand) some six miles north of Blue Water.

Ice Spring Craters, Utah.—About 125 miles south of Salt Lake City and well out in the desert-valley to the west of the bold Wasatch Mountains, there are several craters which derive special interest from their association with the history of an ancient lake which once flooded many of the now arid valleys of Utah. The old lake referred to, named Lake Bonneville,[1] was in existence during the Pleistocene period of geological history; the time that witnessed various advances and retreats of glacial ice over the northern portions of North America. Some of the volcanoes in the valleys of Utah are of more ancient date than the first rise of Lake Bonneville; at least one of them had a period of activity during the time the lake basin was flooded, and several small examples, which form a compact group known as the Ice Spring craters, have come into existence since the water of the old lake disappeared.

The Ice Spring craters (Plate 7) are situated on a broad featureless plain composed of the sediments of Lake Bonneville, known as the Sevier Desert, and are ten miles northwest of the town of Fillmore.

At the locality mentioned, there are three small craters of scoria and lapilli, which are fresh in appearance and

[1] A report on Lake Bonneville by G. K. Gilbert, forms Monograph, Vol. I of the U. S. Geological Survey. The craters mentioned are described on pp. 319–339 of this report.

nearly perfect in form. Closely associated with these and partially concealed by them, are fragments of at least nine other craters of similar character. About this group of volcanic vents there are coulées of basaltic lava which flowed from them at various times and cover an area of 12.5 square miles.

A bird's-eye view of the three well-preserved craters and a fragment of a much larger one named the Crescent, as well as of the lava field to the eastward of the group, is shown in Plate 7. This view here reproduced from Gilbert's monograph, was constructed from sketches, with the aid of an accurate plane-table map, and will serve better than a written description to convey an idea of the leading features of the central portion of the Ice Spring craters.

The Crescent, as just stated, is only a fragment of the crater wall of a volcano which has been more than half destroyed by explosions. In some respects it is to be compared to the rim of ancient date that partially surrounds Vesuvius, and known as Mt. Somma. The Crescent rises 250 feet above its eastern base, and when complete must have had a diameter of about 2200 feet.

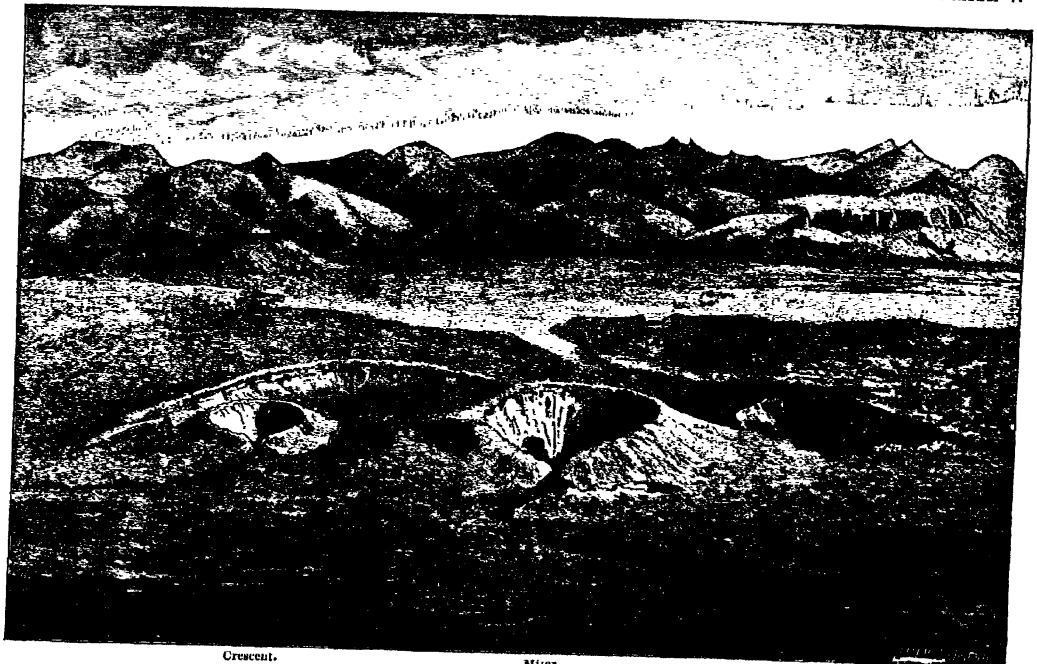
The central crater shown in the illustration, named the Miter, is probably the most recent of the group, as no other crater overlaps it. It rises 250 feet above its west base and 275 feet above the bottom of the pit it encloses. Its rim is nearly circular, and has a diameter of 950 feet. After it had reached approximately its present size, lava rose within it and, breaking through its north side, flowed away as a well-defined stream, which expanded on the adjacent plain. This lava eruption was followed by one of explosive violence, during which the break in the crater

rim was repaired by the deposition of scoriaceous lapilli. The lava again rose in the crater, and again broke through its wall, this time discharging westward, leaving a breach the bottom of which is seventy-five feet higher than the crater's bottom.

Between the Miter and the Crescent is a low cinder cone, resembling the Miter in shape, but only 400 feet in diameter, named Terrace crater, which is well within the area formerly embraced by the Crescent.

The walls of Terrace crater, as described by Gilbert, are for the most part low and characterized by a gentle outward slope. At their culminating point they are scoriaceous, but elsewhere they are of relatively compact lava, with a rude stratification, as though formed by the addition of successive sheets. Its formation was evidently attended by very little explosive action, and there is some ground for believing that its cavity was produced by the fusion of scoriaceous matter, the product of some earlier eruption. Its outline is irregular, with an extreme length of 1100 feet and a width of 700 feet. At one stage in its history it was occupied by a molten lake about fourteen acres in extent, and the partial congelation of the surface of this lake left a terrace at one margin. The subsequent history of the crater includes the formation of four narrow terraces at lower levels. The first lowering of the molten lake appears to have been accomplished by the breaking of the crater wall at the south, and a consequent outflow. The subsequent lowerings were caused by the retreat of the lava down the conduit by which it had originally entered the crater from beneath. This conduit remains open and can be explored for twenty-five feet, when progress is stopped

PLATE 7.



Ice Spring craters, Utah. Bird's-eye view from the west. Wasatch Mountains in the background. (G. K. Gilbert.)

by water. It is a circular tube twelve feet in diameter, and inclined ten or fifteen degrees from the vertical. The stony, arrested drops still pendent from its sides testify by their small diameter to the high fluidity of the lava. The depth of the crater below its general rim is 260 feet, below the sill of its last outflow 220 feet, and below the scoriaceous crag that overlooks it on one side 350 feet.

The streams of basalt flowing from the Ice Spring craters — still quoting Gilbert — have formed two confluent fields, the first extending three and one-half miles northward, with a general breadth of two miles, the second three and one-quarter miles westward, with a general breadth of one and one-half miles. Their area is approximately twelve and one-half square miles. Their marginal depth will average about thirty feet, and their mean depth is estimated at fifty feet. The volume of the ejected material is approximately one-eighth of a cubic mile. The lava is black or dark gray basalt, with exceedingly rough surfaces, due to the breaking of the crust as the still plastic portion beneath continued to flow. In places the surface blocks are piled in confused wave-like ridges, whose crests are twenty or thirty feet above their troughs.

One curious feature of the lava streams that flowed from the Ice Spring craters and fed the surrounding coulée, is that near the craters they are depressed fifteen or twenty feet below the adjacent surface. The appearance is as if the streams of molten rock had eroded channels for themselves. Yet, as stated by Gilbert, the adjacent surfaces resemble very closely the surfaces of the streams. "The explanation appears to be that each

of these outpourings varied in volume, now swelling, now sinking. When most copious, it spread beyond its channel like an aqueous stream and deposited, not its sediment, but its crust. The walls of the channels display a conformatory stratification."

Tabernacle Crater and Lava Field, Utah. — Four miles south of the Ice Spring craters, there is another volcano more recent than the withdrawal of the water of Lake Bonneville, and named Tabernacle crater in reference to its resemblance, when seen from a distance of a mile or two, to the great assembly building in Salt Lake City, known as the Tabernacle.

Tabernacle crater is composed of the same varieties of basalt as the Ice Spring crater, and has two crater rims, one within the other. Surrounding the crater is a nearly circular lava field about three miles in diameter, with an area of approximately seven square miles. The point of issue is not central, but lies near the southeast margin of the lava coulée.

The outer rim of the crater, one-third of which has been removed, has a diameter of 2200 feet and on the highest side rises 120 feet above the surrounding lava fields. The inner rim, composed of scoriaceous material, is complete in general form, but is rough and abounds in pinnacles.

The chief phases in the history of Tabernacle crater, as determined by Gilbert,[1] are as follows: When Lake Bonneville stood at a comparatively low level, known as the Provo stage, it has a depth of from fifty to seventy-five feet above the valley bottom where the crater now

[1] "Lake Bonneville," U. S. Geological Survey, Monograph, Vol. I, pp. 329-332.

stands, and was held at a constant level for many centuries. An explosive eruption occurred beneath the lake, of such violence that the material blown out was deposited most abundantly at a distance of more than a thousand feet from the point of discharge. The rim built up by this explosive eruption eventually rose above the surface of the lake and shut out its waters. The eruption then became less violent, and the material discharged changed, becoming pasty. Quiet eruptions followed, developing a low black island which had a line traced about it by the waves before the lake was finally lowered by evaporation. The declining phase of the eruption was again explosive.

The lava field about Tabernacle crater terminates in most directions in a steep cliff, showing that the lava flowed sluggishly, and was of such consistency as to form a deep stream instead of spreading widely and ending in a thin edge, as is the habit of very liquid lavas. The surface is rugged, on account of the breaking of the crust by the motion of the still liquid portion beneath. The sinking of the blocks formed by the breaking of the crust into the plastic lava, may have increased the friction of flow, and thus caused the flood to advance with a precipitous terminus. The height of the outer escarpment is in places sixty-five feet.

Among the minor points of interest to the student of volcanic phenomena at the Ice Spring and Tabernacle craters, is the presence of lapilli widely scattered on the lava flow, showing the violence with which the fragments were thrown out, although there is an absence of evidence showing excessive energy. Near the craters much of the scoria was ejected in a pasty condition and came to rest

while still plastic. Some of the bombs are possibly a mile from the crater from which they started on their aërial journey, but struck the ground while still plastic, and were flattened so as to form cakes, in some instances between two and three feet in diameter; on the under side they preserve impressions of the rough surfaces on which they fell. Well-formed spherical bombs, characteristic of many volcanic regions, which cool during their passage through the air and sometimes exhibit a spiral twist due to rotation while still plastic, were not noticed.

The surfaces of some of the lava flows, particularly in the neighborhood of the Miter, are exceedingly rugged, on account, as already mentioned, of the breaking of the crust formed on the surface, while the still plastic portion below continued to flow. The rough surfaces thus produced are of the same character as the aa fields of the Hawaiian islands. In some instances about the Ice Spring craters, especially, the under surface of the angular blocks formed by the breaking of the crust are grooved and striated in a striking manner, and show the effect of the friction of the moving undercurrent while the crust was yet plastic at a depth of eight or ten inches below the exposed surface.

The interstices of the lava in the coulée about Tabernacle crater are in some places filled with fine, yellowish dust, which has gained access to steam cavities, through openings too small to be distinguished by the eye.

While the Ice Spring and Tabernacle craters are young as compared with the fall of the water of Lake Bonneville below the lowest notch in the rim of the basin that confined it, yet their absolute age in years cannot be determined. The lavas are fresh in appearance, and no-

where have yielded to the action of the atmosphere so as to form a soil. It is to be remembered, however, that under the dry climate of Utah, such a change is excessively slow, and the fresh appearance of the lava is not an argument in favor of very recent origin.

In the same valley with the volcanoes just described, there is another of older date, named Pavant butte, about which the waters of Lake Bonneville left conspicuous markings. This volcanic pile is formed of lapilli, and furnishes evidence that an eruption took place when the lake was at its highest stage, and beneath a body of water 350 feet deep. The resulting cone was built not only to the surface of the water, but 450 feet higher. Eruption ceased with the fall of the water and has not since been resumed. A detailed and instructive account of this volcano may be found in the report on Lake Bonneville, already referred to.

Craters near Ragtown, Nevada.—The craters in Utah, just described, derive much of their interest, as has been seen, from their association with the history of Lake Bonneville. In Nevada there was another great lake in Pleistocene times, contemporary with the one in Utah, which is known as Lake Lahontan. The Nevada lake also had volcanic phenomena associated with its history.

One of the broadest portions of Lake Lahontan occupied what is now the Carson desert, Nevada. On the inner slopes of the mountains surrounding and nearly enclosing this basin, there are shore lines which show that at one time it was flooded to the depth of 500 feet above the stratified clays now forming its floor. In the western part of the desert, about two miles from a little settlement named Ragtown, and twenty-two miles southeast of Wadsworth,

a town on the Central Pacific railroad, there are two circular depressions occupied by strongly alkaline water, which are termed the Ragtown ponds, or Soda lakes.

These lakes occupy volcanic craters the rims of which rise above the surface of the surrounding sage-brush-covered desert. while their bottoms are depressed below that horizon. The rim of the larger crater, at its highest point, is 80 feet above the desert and 165 feet above the surface of the water within. The water has a maximum depth of 147 feet, making the total depth of the crater 312 feet. Its bottom is 232 feet below the desert's surface. The least diameter of the crater at the water's surface is 3168 feet, and its greatest diameter 4224 feet. The area of the lake is 268.5 acres. The diameter of the crater, measured from opposite points on the summit of its rim, might be variously determined, owing to the lack of a well-defined crest at all places, but in general is about one mile. The smaller lake is much inferior to its companion in all dimensions. Its diameter from points on opposite sides of its low and not well-defined rim, is about one-half mile, and its depth to the shallow pond within, approximately seventy feet.

The measurements just given show that the larger crater is by no means insignificant. The proof that it was produced by volcanic explosions, and also its place in the history of Lake Lahontan, is shown by the following evidence. The general form of the crater, that is, a depression surrounded by a raised rim, is such as frequently results from the blowing out of projectiles when volcanoes of the explosive type are in action. Sections of the wall of the crater show that it is composed of lapilli and volcanic dust, together with numerous

scoriaceous fragments of basalt. The basaltic masses are of all sizes up to two feet in diameter, and occur at all heights in the crater's walls from base to summit, and on the adjacent surface of the desert. Frequently, in the case of freshly exposed basaltic masses in the crater walls, the strata of fine, loose material on which they rest are beat down in the manner that would be expected had the "bombs" been thrown into the air and fallen to their present position from a height of several hundred feet. The layers of lapilli forming the crater's rim are frequently inclined both in the direction of its outer and inner slopes, and are also frequently interrupted or unconformable, portions of the deposit having been removed, as is common in the case of craters that have been partially destroyed by the violence of the explosions from within, and subsequently rebuilt.

Interstratified with the layers of volcanic origin are beds of lacustral clay and deposits of calcareous tufa. The tufa is identical in origin, so far as one can judge, with extensive sheets of the same character occurring at numerous localities throughout the Lahontan basin, and determined to have been precipitated from the waters of the former lake. The evidence is clear that the volcanoes whose craters are now occupied by the Soda lakes, were in activity during the existence of Lake Lahontan, and also that the last eruption occurred since the lake waters fell below the level of the Carson desert. The outer slopes of the crater walls are not marked by terraces, as would have been the case had such piles of loose, incoherent material been exposed to wave action. The volcanoes were of the explosive type and threw out only fragmental material. No lava streams are associated with them.

The Soda lakes are the basis of a considerable soda industry and are of interest also on account of the crustaceans and insects that live in their waters. In the larger lake, crystals of a pure white soda mineral named *gaylussite*, are forming. The composition of the waters of these lakes and other facts concerning their history are given in the books mentioned in the following foot-note.[1]

Volcanoes of Mono Valley, California. — Mono valley is situated at the eastern base of the Sierra Nevada, in about the centre of the eastern border of California, but extends across the interstate boundary into Nevada. In the lowest part of the valley and reaching the base of the steep eastern slope of the Sierra Nevada lies Mono Lake, a body of intensely alkaline water.

The eastern portion of Mono valley partakes of the desert-like character of the great interior arid region of which it is a part; but its western and southwestern portion is well watered by streams which have their sources in the forest-covered Sierra Nevada. Like many other enclosed basins between the Sierra Nevada and Rocky Mountains, Mono valley has an instructive history of climate fluctuations, in the form of terraces, lacustral deposits, glacial moraines, etc., written on its inner slopes, but at present we must pass this by.

In the centre of the lake at the present time there are two islands, named Paoha and Negit islands, besides several rocky crags. We will begin our studies of the instructive volcanic phenomena of Mono valley by examining these islands. Let the reader in fancy take a seat beside me in

[1] Arnold Hague and S. F. Emmons, U. S. Geological Survey of the Fortieth Parallel, Vol. II, 1877, pp. 744–750. Clarence King, U. S. Geological Survey of the Fortieth Parallel, Vol. I, 1878, pp. 510–514. I. C. Russell, "Lake Lahontan," U. S. Geological Survey, Monograph, Vol. XI, 1885, pp. 76–80.

a small boat, with a single Indian from the encampment on the shore to use the paddle, and I will endeavor to point out some of the more instructive features that present themselves as we glide over the placid surface of the lake, on our way to the islands.

The water over which we pass gives the fingers a slippery feeling; if we taste it we find that it is intensely alkaline and bitter. As we look down into the water we see that it is clear and limpid, but the view is usually obstructed by countless numbers of brine shrimps (*Artemia*) and the larvæ of flies. The lavæ are thrown ashore by the waves in windrows that are frequently a foot or more deep. The lava cases on drying are detached from the dried worms within and may be easily separated On the sloping sandy shore near an encampment, you may see a number of Indian women with large conical baskets on their backs, and a second shallow paddle-shaped basket in their hands. With the flat basket they throw the dried larvæ in the air and allow the wind to carry away the chaff-like cases. The desiccated worms are then transferred to the baskets on their backs, to be used as food.

On the borders of the valley we can see the horizontal lines at various heights that mark the level of the water in former times. The highest of these lines, which is drawn about the steep faces of outstanding bluffs and continued into the lateral valleys between, is 675 feet above the present lake surface, but is not now perfectly horizontal. A movement in the rocks has taken place since the lake was at its highest stage. The differences in elevation at various points in the old beach line, however, are not over fifteen or twenty feet.

The scene that invites the attention of the traveller in Mono valley to the exclusion, for a time at least, of all other features, is the range of magnificent mountains that limits the view to the southwest. The surface of the lake is 6380 feet above the sea. The highest of the serrate peaks, Mt. Dana, rising precipitously from its border, reaches 6612 feet above us, and is 12,992 feet above the sea. Twelve miles south of Mt. Dana and also on the rim of the basin surrounding Mono Lake, stands Mt. Lyell, 13,042 feet in height, amid a group of white cathedral-like spires that are but little inferior to it in elevation. On the northern sides of several of the higher peaks in view there are small glaciers, which contribute the water formed by their melting to the swift streams supplying Mono Lake. In the deep gorges excavated in the sides of the mountains we can distinguish the rounded contours of the valleys due to the broadening and smoothing of stream-cut valleys by ancient glaciers. When the gorges open out into the plain bordering the lake, they are conspicuous moraines, which in several instances are prolonged from the entrances of the high grade-valley, as parallel morainal embankments, more than a thousand feet high, which were deposited on the border of the ancient glaciers after escaping from the confinement of the mountain precipices.

To the south of the lake, and separated from the rugged eastern face of the Sierra Nevada by an extension of Mono valley, rises a conspicuous range of volcanoes which furnish some of the most pleasing and instructive features in the diversified landscape. These volcanoes are known as the Mono craters, and will be examined after our visit to the islands which in fancy we are nearing.

The larger of the two main islands is mild in relief and almost white in color, while the smaller one is rugged and nearly black. These differences have an intimate connection with their origin and geological history. In seeking for a name by which to designate the islands, during my exploration of Mono valley, it was suggested that their contrasts in color might be used, but I preferred to record some of the poetic words in the language of the aborigines who still inhabit the valley. On the larger island there are hot springs and orifices through which heated vapors escape. These hot springs and fumaroles are the lingering remnants of volcanic energy which, in times not remote, built some of the most conspicuous landmarks in the valley. It seems fitting that the words of the Pa-vi-o-osi people, who, like the volcanic energy, are fast passing away, should be attached to the scenes with which they have long been familiar. Among the legends of the aborigines there is one concerning diminutive sprites having long, waving hair, that were sometimes seen in the vapor-wreaths escaping from the hot springs. The word *Pa-o-ha*, by which these elves were known, is also used to distinguish the hot springs themselves. We therefore named the larger island in memory of the children of the mist that hold their revels there on moonlit nights, Paoha Island.

The island near Paoha Island, and second to it in size, has been called Negit Island, *Negit* being the Pa-vi-o-osi name of the blue-winged goose.

On reaching Paoha Island, we find shelter for our boat in a cove on its eastern side, which we recognize at once as being a partially submerged crater of basaltic lapilli. The side of the crater facing the lake has been broken

down, and the lake water now extends into the cavity kept open at the time the crater was formed by the violently escaping steam.

On walking over Paoha Island, we find that the whiteness of its surface, which we noted on approaching, is due to a thick deposit of lacustral clay and marl, together with considerable quantities of volcanic dust, which was showered down on the lake when its surface was considerably higher than at present and the island was completely submerged. On the surface of the lake beds and evidently dropped there since the island was left exposed by the recession of the lake, we find masses of scoriaceous basalt, which become more and more numerous as we approach an elevation on the northeast extremity of the island and only a quarter of a mile north of the cove in which we landed. Mingléd with the blocks of basalt are numerous rounded and water-worn pebbles of granite and other rocks, which one familiar with the geology of the Sierra Nevada will at once recognize as being similar to the rocks there exposed and identical with the pebbles in the streams that flow from the mountains. As these pebbles, like the blocks of volcanic rock with which they are mingled, do not occur in the lacustral sediments, so far as we can discover, it is evident that they reached their present resting-place at a recent date. Since the pebbles are not covered by lake sediments but rest on them, they must have been brought since the island emerged from the water. Without going over all the steps in the evidence by which an explanation of the presence of the pebbles was reached, I may say that in company with the blocks of basalt and much lapilli and dust associated with them, they were blown out of a crater on the

island, and fell on the adjacent surface at a recent date. The crater from which they came forms the hill already mentioned, on the northeast point of the island. A map of this locality, including also the partially submerged crater in which we left our boat, is given below.

In further explanation of the presence of the pebbles referred to, I may say that similar water-worn rocks occur on the neighboring Mono craters even to their summits. Previous to the origin of Mono Lake or dur-

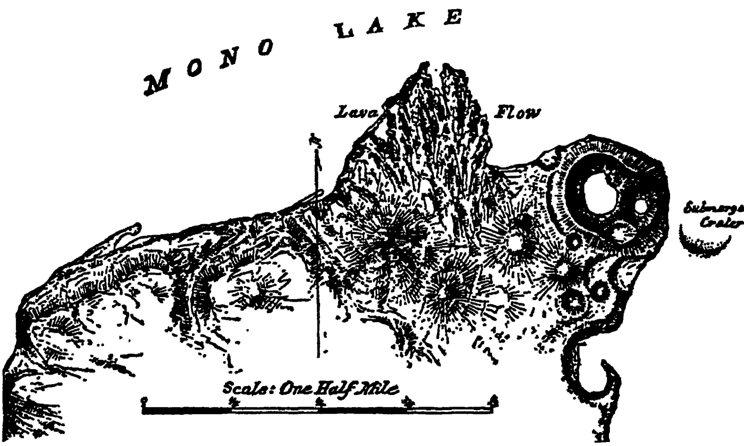


FIG. 7. North end of Paoha Island, Mono Lake, Cal. (Surveyed by W. D. Johnson.)

ing a period of low water in its earlier history, the streams from the mountains spread a sheet of gravel over the valley. The volcanic vents were opened through this deposit, and the violence with which steam escaped, carried the stones upwards in much the same manner that volcanic bombs are projected out of volcanic vents, and scattered them over the adjacent region. These pebbles of granite are similar, so far as their connection with the volcanoes of Mono valley is concerned, with the blocks of limestone thrown out by Vesuvius. At Vesuvius the

volcanic conduit traverses limestones, portions of which are torn off by the violent uprush of steam or forced into the conduit by steam explosions from its sides; in Mono valley the volcanoes opened conduits through a stratum of gravel and rounded boulders, some of which were carried to the surface with such violence that they were projected high in the air, and fell about the craters.

Each of the bowl-shaped depressions shown in the accompanying sketch-map is a crater of recent date. They do not contain lacustral clays and are not scored with beach lines on their outer slopes. The loose incoherent nature of the material of which they are composed renders it evident that they could not have withstood the action of waves and currents for even a brief period without having evidence of the fact inscribed upon them. They are, therefore, more recent than the last high-water stage of Mono Lake.

The largest crater is from 150 to 175 feet deep. The regularity of its outlines has been broken by the formation of two smaller craters on its rim. The narrow ridge of lapilli separating the main crater from its larger parasite, forms a symmetrical curve, as it descends from one end of the broken rim of the older crater and ascends to the opposite extremity. The craters separated by the low wall hold lakelets of strongly alkaline water, whose surfaces are on a level with Mono Lake, from which they are supplied by percolation. The waves of the surrounding lake have carved away the base of the outer slope of the crater on the north and east, and made it precipitous, and will no doubt soon open breaches through it, so that the lakelets will have open connections with the surrounding waters. A submerged crater a few rods from shore,

revealed by soundings, shows that one member of the group has perhaps already succumbed to the attack of the waves, or else was formed by explosions beneath the lake's surface.

On the west side of the craters described above, there is a small lava flow, also shown in Fig. 7, which descends into the lake. That this lava stream was formed at a recent date is at once suggested by the fresh appearance of the black, angular blocks composing it. The lava is not covered with lacustral sediments, and is without certain calcareous incrustations, which are common on similar rocks in various parts of the valley below the ancient beach lines that record the former horizons of the lake's surface. The lava flow is, therefore, more recent than the latest high-water stage of the lake. It is also of more recent origin than the neighboring lapilli craters, as its surface is free from the débris showered over the island when they were formed. The lava descends into the lake without change of character, thus indicating that the surface of the water, at the time of its extrusion, was lower than now. The distinctions, however, between the characteristics of a subaërial and a subaqueous lava flow are not sufficiently well determined to allow one to decide in all cases in which manner an eruption occurred.

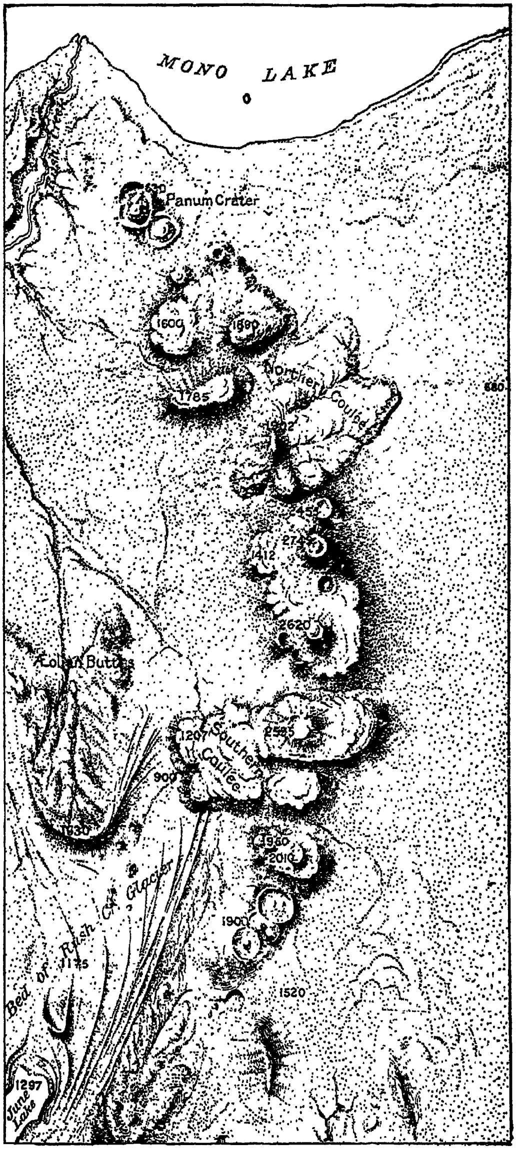
The central portion of the small lava flow just described is lower than its sides. After the sides and surface had cooled and hardened, the still liquid interior flowed out and allowed the surface crust to subside. On looking down on the surface of the lava stream from the adjacent elevations, another interesting fact is to be noted. The apparent chaos of angular blocks composing it, is not in reality without some order. The larger blocks are heaped

in crescent-shaped ridges, which cross the stream and are convex in the direction of flow. Several of these curved ridges may be easily distinguished, which are concentric, one with another, and resemble in a general way the curved terminal moraines to be seen in many formerly glaciated valleys. The wave-like appearance of the surface of the lava flow is due to pulsations in the stream of molten rock, caused by the clogging of the current by the blocks of hardened lava floating on its surface.

The rock forming the lava flow just described has been studied by Professor J. P. Iddings, and found to be essentially a hypersthene andesite, although its microscopic structure is somewhat indefinite. It is on the dividing line between andesite and basalt, but apparently the weight of evidence places it in the former. It is a black, fine-grained, compact rock, breaking with a conchoidal fracture, and to the field geologist has all the appearance of basalt, but is free from olivine.

This outwelling of lava came from near the base of the lapilli crater described above. It is the latest extruded material on Paoha Island, and probably the last igneous discharge in Mono valley.

Negit Island is composed of a crater, and of a coulée of lava which extends a third of a mile southward from its base. The recent origin of the island is attested by the absence of lacustral deposits, but a thin coating of calcareous tufa extending twenty feet above the 1883 level of the lake, shows that the coulée is of somewhat older date than the similar lava streams on Paoha Island. The rocks composing Negit Island are even more basaltic in appearance than those of its neighbor, but are classed by Iddings as hypersthene andesite. The crater is unlike any



MONO CRATERS

0 2 3 4 MILES.

Elevations above Lake Mono given in feet.

other in Mono valley, and is not a lapilli cone, but is composed of scoria, which was ejected in large semi-plastic masses. No dust or lapilli is scattered over the rugged surface of the black lava.

The crags and isolated rocks in Mono Lake to the north of the two principal islands, are fragments left by erosion of ancient mica andesite (also a volcanic rock) similar to the basement rock beneath the lacustral marls and recent lapilli deposits of Paoha Island.

From the Negit Island southward to the end of the Mono craters, when they come down nearly to the lake shore, is but a little over four miles. When the wind is fair, this distance is quickly sailed. On approaching the shore, we find it fringed with a broad belt of white froth. The alkaline waters are easily churned into foam, which after a gale is frequently two or three feet deep, and is blown ashore in cotton-like masses, that are rolled along by the wind, and even reach the desert vegetation fringing the desolate area near the lake shore. Let us continue our excursion by ascending the Mono craters.

The Mono Craters.—The grouping of these craters and the positions of the coulées of lava that have flowed from them are shown on the map forming Plate 8. They form a slightly crescent-shaped range of mountains, extending south from Mono Lake to a distance of about ten miles. More than twenty complete or partially buried craters can be recognized. Others are no doubt concealed beneath the products of the more recent eruptions.

The highest, and, judging from their eroded condition, the oldest, of the well-defined cones in the range are in its central part. The four higher summits rise in order from north to south, 2455, 2749, 2620, and 2595 feet, respec-

tively, above the surface of Mono Lake, which, as previously stated, is 6380 feet above the sea.

The Mono craters are composed largely of clastic material, of which a light gray lapilli forms the greater part. There are also several coulées of lava which flowed out in a molten condition and consist, in large part, of a dense black glass termed *obsidian*. These two methods of extrusion have produced striking contrasts in the form and color of various portions of the range.

The accumulations of lapilli have a light gray tint, and smooth, even contours. All of the cones are composed, to a large extent, of this material and are especially pleasing and beautiful to the eye on account of their graceful curves and soft, harmonious tints. In marked contrast with the lapilli deposits are thick sheets of black obsidian of recent date, which have flowed in various directions and usually from near the crest of the range. The surfaces of these overflows are angular and rugged to the last degree. As shown on the accompanying map, one of these outpourings of volcanic glass occurs near the southern end of the range of craters, and another of less size near its northern end.

Owing to the highly viscous condition of the lava of these coulées at the time of its extrusion, it formed thick sheets, which terminate in precipices between 200 and 300 feet high. The slow-moving lava congealed and came to rest on slopes so steep that it seems almost a miracle that they should have remained in such positions.

The contrast presented by the lapilli deposits and coulées, which consist of the same magma cooled under different conditions, is most striking. The fragments composing the former are open in texture, vesicular,

light-colored, and form smooth, even slopes with inclinations of about 30°; the obsidian is a dense, black glass without cavities or steam blebs, but abounds in stony inclusions, and frequently has its surface dusted over with lapilli that fell upon it while it was still somewhat plastic.

The Mono craters are markedly different from any other volcanoes in the United States now known. The rock composing them is a rhyolite, and is highly acidic. It presents marked contrasts to the basic material composing the great majority of recent volcanic rocks the world over. The volcanic history of Mono valley will repay more careful study than it has thus far received, for the reason that the phenomena there so well displayed are, in a great measure, unique.

As previously stated, the lofty central cones in the Mono craters are considerably eroded and have lost their craters. Their summits are blunted and the removal of lapilli has exposed crags of rough lava. The volcanic energy early in the history of the range, evidently found an avenue of escape where the central cones now stand; and when the conduits of these craters became clogged, newer craters were formed both to the north and south along the same line or belt of fracture. In general, the craters appear fresher and fresher the more remote they are from the centre of the range. A good illustration is thus furnished of the well-known fact that volcanoes are frequently located on fissures and that when one conduit becomes closed others are opened along the same line of fracture. More could be said in this connection in reference to the volcanoes of the Mono region, since the Mono craters, although a unit in themselves and forming an

isolated and well-defined group, are in fact a portion of a much more extended series of recent eruptions, which follow the general course of the great belt of branching faults which determines the eastern face of the Sierra Nevada. The craters on the island in Mono Lake are on this belt of disturbance. Northwest of the lake there are other volcanoes. South of the Mono crater the same belt of recent cones is continued and is marked by recent craters of both acidic and basic lava, for at least a score of miles.

There are some exceptions to the statement that the most recent eruptions occurred at the ends of the Mono craters, since two or three of the smaller craters near the centre of the range and high up on the flanks of the large central cones, are fresh in appearance and possibly as recent as the vents at the extremities of the series.

The craters which still preserve their shapes and show but slight evidence of having been modified by erosion may, for convenience of description, be divided into two groups, although in reality there is no true dividing line between them. In the case of the craters forming the first of these groups, the lapilli fell on all sides of the place of extrusion and built up symmetrical rings, enclosing conical basins. Some of these are depressed bowls with scarcely a vestige of a raised rim about them; while others are well-defined cones rising steeply from the surrounding surface, and have deep conical depressions in their summits. The craters of the second group are similar to those just mentioned, except that they gave egress to molten lava.

The craters that were points of eruption for both lapilli and lava may again be divided into two groups: (1) Those

in which the lava did not escape from the bowls formed by the violent extrusion of fragmental material, and (2) those from which the lava overflowed and formed more or less extensive coulées. As may be seen at a glance, these variations depend simply on differences in the intensity of the volcanic activity. The first eruption in each instance was a violent ejection of comminuted and usually scoriaceous, but at times compact and glassy rhyolite. In the craters formed entirely of lapilli, the eruptions ended at this point. In other instances, an escape of viscid lava took place through the same conduit from which the lapilli came. In some cases when an upwelling of lava occurred, it barely entered the bottom of the bowl of lapilli before becoming congealed. The eruption then ceased, so far as that individual vent was concerned. At other times, the thick, viscid lava was forced up in the centre of the crater until it stood higher than the encircling rim of lapilli but did not expand laterally. In instances of this nature there is a deep, moat-like depression between the rough and angular protrusion of lava and the smooth inner slope of the encircling crater, in which one may walk entirely around the central tower-like mass. The type of this variety of eruption is furnished by the crater shown in the following illustration, which stands near the shore of Mono Lake and has been named Panum crater.

Where the upwelling of lava was larger in amount, it broke through the encircling rim of lapilli and flowed away as a stream, or coulée, of lava, which, on account of its viscous nature, — characteristic of all the lava flows from the Mono crater, — ended in a steep border composed of angular blocks. The surfaces of the streams,

in all cases, also, are of this same character; their broken and angular condition being due to the rapid cooling of the lava at the surface, while the interior was still plastic and moving. The surfaces of the streams are sometimes highly vesicular, and so filled with steam bubbles that the rock is a true pumice; at other times, especially in the case of the larger streams, the blocks are of dense black obsidian. To walk on the chaos of angular fragments, in the latter instance, is like crossing a field covered deeply with huge blocks of broken glass.

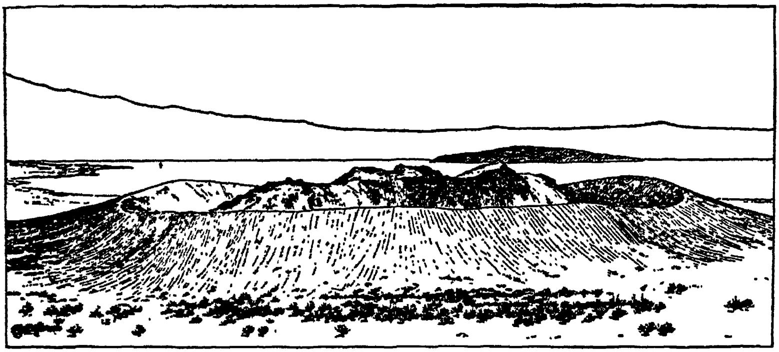


FIG. 8. Panum Crater: Lake Mono and Paoha Island in the distance. (From a photograph.)

Some of the variations presented by the Mono crater, due to differences in the relative amounts of lapilli, and of lava extruded, are indicated in the following series of cross-sections of a few of the craters. These are sketch sections and are not drawn to a uniform scale.

In the diagram, *a* is a depression in a field of lapilli, and has a level floor of the same material; *b* is a lapilli crater, also floored with material of the same character as that forming the rim; *c* is a crater similar to *b*, except that a few crags of scoriaceous rhyolite in its bottom mark

the position of the summit of a plug of hardened lava, that exists beneath; in the crater marked *d*, the lava has risen so as to be higher than the wall of lapilli encircling it; this is intended to show the condition existing in Panum crater, illustrated also on Plate 8. A continuation of the series might be made by adding cross-sections of craters in which the lava has broken through a rim of lapilli and advanced on the adjacent surface. Figure *e* illustrates still another variety of crater which is represented by at least one example, the steep-sided depression in this instance is due to the subsidence or retreat of the lava which

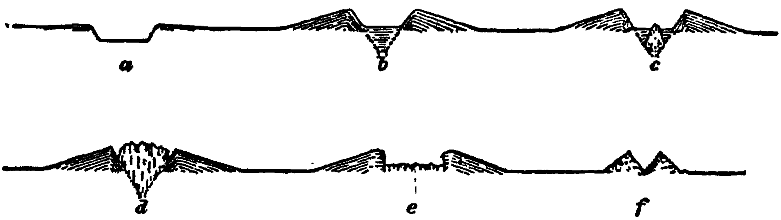


FIG. 9. Cross-sections of some of the Mono craters.

once rose within a crater of lapilli. Figure *f* is a small cone composed of scoria which was thrown out in a plastic condition and piled up around the vent. The last example occurs at the edge of a coulée, at the north end of the range, and is about seventy-five feet deep.

The craters in which volcanic action was most energetic gave origin to coulées of lava, as already stated. When this occurred, the craters of loose incoherent lapilli were breached and sometimes entirely destroyed. One of the smaller lava flows near the north end of the range may be traced directly to the crater from which it originated, of which only a small portion now remains. In the case of the larger overflows, designated on the accom-

panying map as the Northern and Southern coulées, no vestiges of the crater from which the lava came can now be seen. The obsidian composing these streams was extruded in a thick, viscid condition, and flowed slowly down the steep mountain side. The Northern coulée congealed before reaching level ground, but the Southern coulée, after descending the mountain slope, advanced nearly a mile on the plain and finally came to rest with a steep and exceedingly rugged outward-forcing escarpment.

As shown on the map, the Southern coulée invaded a region formerly occupied by a glacier, and obliterated the upper portion of a deep stream-channel made by the water that flowed from the melting ice. The smooth, evenly curved ridges sweeping out from the vicinity of June Lake, shown in the southwest corner of the map, are moraines left by a large glacier. The lava stream is more recent than the recession of the end of the glacier, the bed of which it now occupies, and of late Pleistocene age.

Additional evidence that some of the Mono craters were in a state of violent eruption after the existence of the glacier of the Sierra Nevada, is furnished by deposits of fine, nearly white rhyolitic dust, which cover several of the moraines in the southern portion of Mono valley. Similar dust deposits are strewn for hundreds of square miles over the adjacent region. These will be described, together with other similar accumulations, in a future chapter. As is represented also on the accompanying map, there is a small crater half a mile north of June Lake, which was formed previous to the advance of the glacier referred to above, and was partially removed by the ice which flowed over it.

Other features of Mono valley which are of interest to

Mt. Shasta, California, from the east. (Photograph by U. S. Geological Survey.)

the student of volcanic phenomena might be described, but as one of the objects of this book is to lead the reader to consult original monographs, I must refer those who desire to pursue the subject further, to the report from which the data given above has mostly been taken.[1]

Mt. Shasta, California. — In travelling northward through the broad Sacramento valley, one has before him a lofty, snow-crowned, conical mountain, which stands alone and is the dominant feature in the landscape. This attractive object is Mt. Shasta, a typical volcanic mountain. The main summit has lost the freshness of youth and is seamed with radiating ravines and gulches, which have resulted from the work of streams and glaciers. Some of these features may be recognized in the photograph forming Plate 9.

Mt. Shasta has an elevation of 14,350 feet, and towers a mile in vertical height above its nearest neighbor. The summit is more than 4000 feet above the timber line, and is occupied by small glaciers.[2] The upper 3000 feet of the mountain's side, where cliffs are most abundant, has an average slope of nearly 35°; farther down, the inclination becomes more gentle. The base of the mountain is seventeen miles in diameter, and its altitude above its base, or its visual height, is over two miles. Its volume is in the neighborhood of eighty-four cubic miles.

On the west side of Mt. Shasta, 2000 feet lower than the main summit, is a well-developed cone with a crater in its top, known as Shastina. On the lower slopes of the

[1] I. C. Russell, "Quaternary History of Mono Valley, California," in 8th Annual Report of the U. S. Geological Survey, 1886–87.

[2] These glaciers are described in "Glaciers of North America," by I. C. Russell, pp. 55–62. Ginn & Co., Boston, 1897.

mountain, and in the region surrounding it, there are a number of smaller craters, some of them built of cinders, and others of lava. The mountain is composed of lava flows with a minor quantity of scoria.

On the flanks of Shasta there are well-defined lava streams which still retain the rough, angular surfaces given to them when the viscid magmas flowed out and cooled in thick sheets which terminate on steep slopes with precipitous terrace-like borders. One of these coulées on the northwestern side of the mountain, and at an altitude of from 5000 to 6000 feet, forms what has been named Lava Park. Judging from the freshness of the rock, this is the youngest coulée on the mountain. The slope over which the lava flowed was comparatively gentle, so that it spread broadly, and formed a sheet nearly as wide as long. The park is an exceedingly rough lava field, about two square miles in area, on which so little soil has formed that forest trees have not taken root. The lava at the time of its extrusion was viscous, and on coming to rest formed a steep escarpment about its lower margin.

Another conspicuous coulée similar to the one forming Lava Park escaped from the western side of the mountain at an elevation of 5000 feet, and followed northwestward in a rather narrow stream for several miles.

The longest and most copious of the more recent lava streams that flowed from Mt. Shasta issued from its southern side at an elevation of about 5500 feet. This stream divided into two branches, one of which is twelve miles long; the other entered the canyon of Sacramento River and reached a distance of fifty miles from its source before cooling checked its advance. That the lava stream

which displaced Sacramento River is of somewhat ancient date, as measured in years, is shown by the amount of erosion it has suffered. Not only has the river cut through the hardened lava, partially filling its ancient channel, leaving portions of the lava rock as a terrace on the border of the canyon, but has excavated a narrow gorge more than a hundred feet deep into the rocks beneath.

The lava streams mentioned above show no evidence of having been glaciated, but retain their original roughness of surface. They are considered as being of more recent date than the time when the glaciers flowing from the summit of the peak reached the plain below. That is, the most recent lavas were poured out subsequently to the Glacial epoch.

As shown by J. S. Diller, the post-glacial coulées, however, form only a thin cover on the slopes of Mt. Shasta. The great mass of the lava composing the mountain was extruded previous to the last great climatic change which enabled the glaciers starting at its summit to flow to the plain below. Although the great body of the mountain is made up of coulées of lava, it contains a large proportion of fragmental material, and must be considered as a mixed or compound cone.

As already stated, Mt. Shasta is a double cone, — Mt. Shasta proper, and Shastina. These two summits are so closely united that they make but one cone below an altitude of 10,000 feet. Besides the two principal vents there are remnants of more than a score of subsidiary ones which contributed to the upbuilding of the mountain. Many other secondary points of eruption are no doubt concealed beneath the great coulées now forming the outer sheathing of the great cone.

The careful studies of Mt. Shasta conducted by Diller have shown that it is composed of many varieties of volcanic rock. Its chief constituents, however, are andesite, rhyolite, and basalt. The most abundant rock is hypersthene andesite — a lava containing little or no hornblende, but much hypersthene. It ranges in color from light and dark gray, often reddish, to black. Basalt occurs only on the lower slopes of the mountain, but forms nearly all of the numerous cinder cones on the adjacent plain.

One of the interesting features of the lower slope of the mountain is Pluto's cave, formed by the flowing out of the central portion of a lava stream after its surface had cooled and hardened. This cave where best developed is from sixty to eighty feet in height, from twenty to seventy broad, and has been followed for nearly a mile without finding its extremity. The floor of the cavern is nearly flat and covered with débris that has fallen from the sides and roof. The roof above it is from ten to seventy-five feet thick, and the lava of which it is composed is full of cavities formed by the expansion of steam while the magma was still plastic.

Many other interesting and instructive facts concerning Mt. Shasta may be found in the graphic and most attractive monograph from which this account has been largely compiled.[1]

Cinder Cone, near Lassen's Peak, California. — The Lassen's peak district is situated in northern California between the Sacramento valley and the broad area of

[1] J. S. Diller, "Mount Shasta, a Typical Volcano," National Geographic Monographs (published under the auspices of the National Geographic Society, by the American Book Co.), Vol. I, 1895, pp. 237–268.

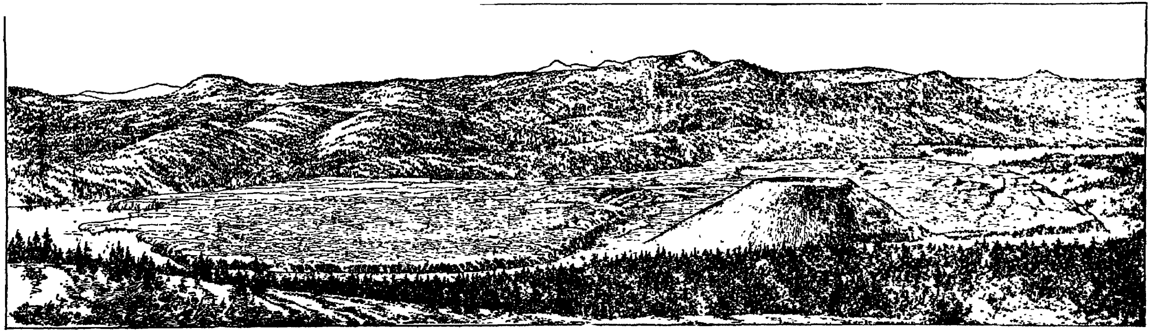


FIG. A. The Cinder cone and lava field near Lassen's Peak, California. (J. S. Diller.)

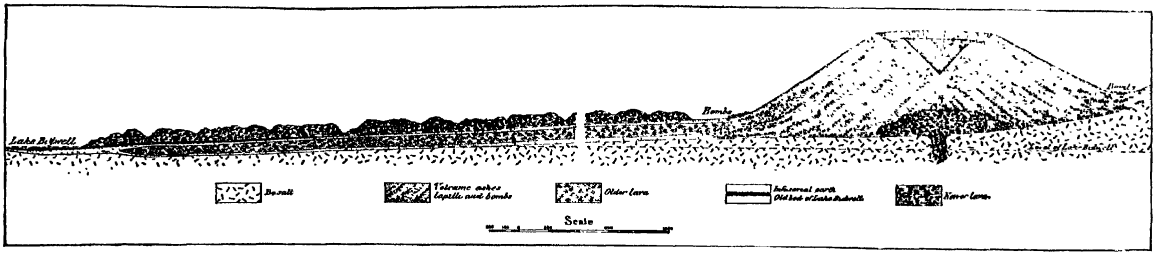


FIG. B. Section through the Cinder cone and lava field near Lassen's Peak, California. (J. S. Diller.)

interior drainage to the east, known as the Great Basin. The volcanic peak from which the district derives its name rises 10,437 feet above the sea, and is considered as marking the southern terminus of the Cascade Mountains.

The Lassen's peak district is crossed from northwest to southeast by a belt of volcanic cones, about fifty miles long and twenty-five miles wide. The great peaks which form the dominant features of this ridge are Butte mountain, Lassen's peak, Crater peak, and Burney butte. Besides these there are many smaller conical hills, which are also of volcanic origin.

By far the most abundant rocks in the Lassen's peak district are those that have cooled from a fused condition and are both intrusive and extrusive. They exhibit great variety, on account of differences in structure and in mineralogical and chemical composition, and range from basalts having as low as forty-nine per cent of silica, through andesites and dacites to rhyolites, some of which contain over seventy-four per cent of silica.

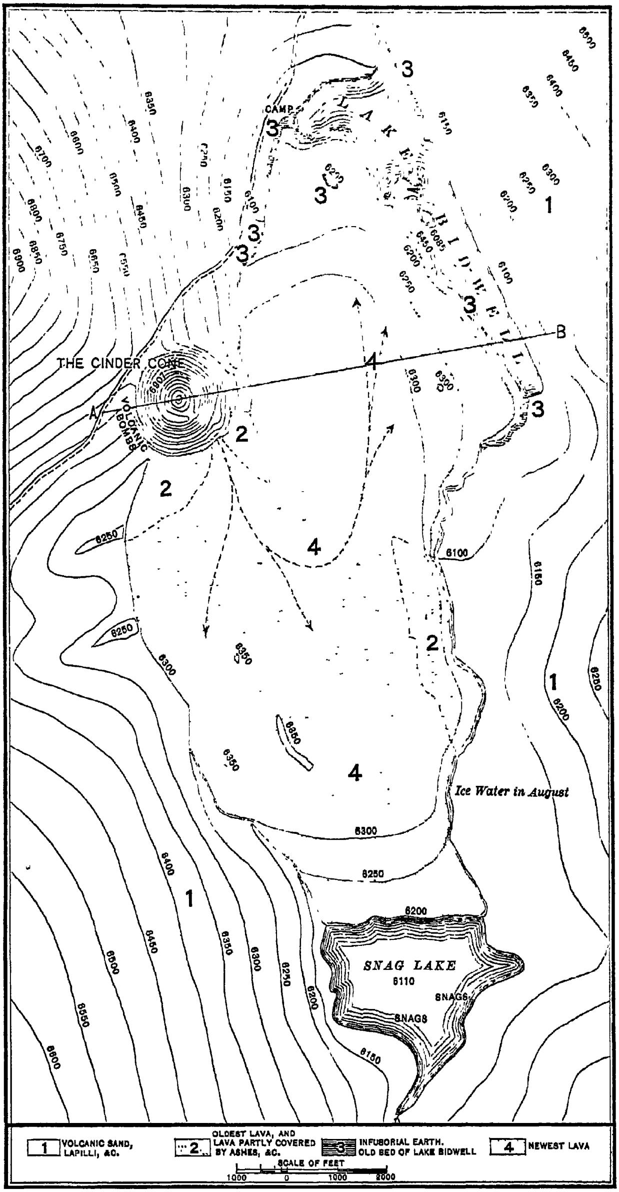
The latest volcanic eruption in the district briefly described above, occurred at what is known as the Cinder cone, ten miles northeast of Lassen's peak. A general view of this locality, taken from a neighboring summit to the northward, is shown on Plate 10, Fig. A. A map of the same locality is presented on Plate 11. As shown in these illustrations, the most striking topographic feature of the region is a conspicuous and very characteristic cinder cone, from the base of which a rugged and exceedingly fresh-looking lava coulée has flowed and spread out over the adjacent plain.

On approaching the Cinder cone one finds the surface,

where not occupied by lava, to be covered with soft, dull, black, volcanic sand. At first this deposit is only a few inches thick, but near the base of the cone it becomes coarser and deeper. What thickness it attains in the immediate vicinity of the cone is unknown, but one-fourth of a mile away in all directions, it is about seven feet deep and decreases in abundance gradually so as to disappear at a distance of eight miles. Encircling the Cinder cone at its base, is a collection of volcanic bombs, ranging in size from a few inches to eight feet in diameter. They are much fissured, and many of them have fallen to pieces, showing an interior of compact lava, while the surface is somewhat scoriaceous and ropy.

On climbing the Cinder cone, one finds it to be composed of loose scoria and lapilli. In form and composition and in fact in all its essential features, it resembles the summit portion of Vesuvius. The cone is regular in form, with a surprisingly smooth, dark surface, and shows no traces of waterways or other evidences of erosion. It rises to an elevation of 640 feet above the lowest point at its base, which is 6907 feet above the sea. Its diameter at the base is 2000 feet and 750 feet across the truncated summit. The slopes are as steep as it is possible for the material of which it is composed to lie, and in places is marked by slides. The angle of slope varies from 30° to 37°. The dull, sombre aspect of the smooth, barren slope is greatly relieved by carmine and orange colored lapilli on its southeastern side.

At the summit of the cone, as shown in the following illustration, there is a well-developed crater with a double rim. The central funnel-shaped depression is 240 feet deep.



Geological map of the Cinder cone region, California. (J. S. Diller.)

The lava field about the Cinder cone has an area of about two and one-third square miles, and at its borders terminates in precipitous scarps, in places over 100 feet high. Within the lava field and about its borders in certain places, there are deposits of soft white diatomaceous earth. This is a lacustral deposit, composed largely of the siliceous cases of unicellular plants, known as diatoms, and is at least ten feet thick. The bearing of this deposit on the history of the volcano will be seen in the following summary, published by Diller, in the geo-

Fig. 10. Sketch of the crater of the cinder cone near Lassen's peak, California, showing the peculiar feature of two rings, of which the inner one encircles a funnel 240 feet deep. (J. S. Diller.)

logical folio where the facts just enumerated are described and discussed.[1]

"The facts just mentioned show that there were at least two periods of eruption from the Cinder cone, and that they were separated by a time interval sufficiently long to allow ten feet of infusorial (diatomaceous) earth to accumulate on the ancient bottom of Lake Bidwell. The first period was characterized by a violent explosive eruption, which formed the Cinder cone and ash field; the second, by a quiet effusion of a large mass of lava.

[1] J. S. Diller, "Geological Atlas of the United States" (published by the U. S. Geological Survey), Lassen peak folio, 1895. This folio contains excellent topographical and geological maps of the region about Lassen peak, and a condensed account of the geology of the region.

"The first eruption began with an explosion and the ejection of a great deal of light scoriaceous, almost pumiceous material, blown chiefly by escaping steam from the upper portion of the molten lava (magma) in the throat of the volcano. Succeeding the explosion and the eruption of the pumiciform material, and continuous with it, came the volcanic sand, lapilli, scoriæ, and bombs. They fell about the hole from which they were blown, and by their accumulation built up the Cinder cone, which is composed almost wholly of fragmental material.

"After the greater portion of the fragmental material had been ejected the magma rose in the Cinder cone, and bursting it asunder, flowed over the southeastern portion of its base. This effusion was accompanied and succeeded by a shower of sand, which may have given rise to the inner rim of the crater, and formed a thin coating over the lava already effused. Whether or not the effusion of the oldest lava and the succeeding shower of ashes belong to the closing stages of the first eruption is not easily determined, but it is certain that both preceded that long interval of quiet during which the old lake beds were deposited. This season of volcanic rest was probably at least a century long, for to accumulate ten feet of infusorial earth would require considerable time.

"The new flow of lava, . . . occurred at the close of the lake-bed interval. The remarkable characteristic of this eruption as compared with the former was the entire absence of any explosion from the crater in connection with the effusion of so large an amount of very viscous magma, since the same vent at an earlier period had been the scene of a violent ejection.

"Everywhere in the lava field one is impressed with

the idea that the lava of this final eruption moved slowly and with great difficulty, repeatedly breaking its crust and pushing along as a great stone pile, presenting an abrupt terrace-like front on all sides. It is a typical example of a lava field formed by the effusion of a viscous lava on gentle slopes. Had it been highly liquid, like many of the other basalts in the same great volcanic field, it would have found egress at the outlet of Lake Bidwell, and stretched down the little valley for miles to the northwest.

"The whole aspect of the Cinder cone and lava field is so new that one at first feels confident of finding historic evidence of its eruption. . . . Yet the evidence clearly demonstrates that the earliest eruption occurred before the beginning of the present century.

"Its age is shown by the relation of the old and new forest trees to the volcanic sand of the first eruption. The living trees grew upon the top of the sand, but the dead ones in the foreground were standing at the time of the eruption, and instead of growing upon the sand, grew from the soil which now lives beneath it."

The evidence furnished by the partially buried trees, etc., as stated by Diller, shows that the first eruption occurred some two hundred years and the second more than fifty years ago.

The Great Volcanic Mountains of Oregon and Washington

Distant views of the Cascade Mountains show that they are dominated by a series of giant peaks, some of which, as Mt. St. Helen's and Mt. Rainier, are detached from

the main mass, while others are intimately associated with the uplifted lava sheets which compose a large part, but more especially of the southern half, of the range.

The greater volcanic cones which form such a pronounced and attractive feature of the Cascade region have never been carefully studied, and only a general account of their more salient features can be given at this time. The peaks, referred to in the order of their occurrence from south to north, are as follows; the figures accompanying the names of the peaks show their height above the sea in feet. They are: Mt. Pitt, 9760; Mt. Mazana, 8223; Mt. Union, 7881; Mt. Scott, 7123; Three Sisters, Mt. Jefferson, 10,200, and Mt. Hood, 11,225, in Oregon; Mt. Adams, 9570; Mt. St. Helen's, 9750; Mt. Rainier, 14,525, and Mt. Baker, 10,877, in Washington.

The conclusion that these peaks are of volcanic origin rests, in some instances, on their general appearance, and their occurrence in a volcanic region, rather than on definite reports by skilled observers. The only ones, however, in reference to which doubt may possibly be entertained respecting their volcanic origin, are two or three of the more southerly ones in Oregon.

None of the mountains named are examples of especially fresh volcanic piles, although nearly all of them are known to have craters at their summits, or on their flanks. Like Mt. Shasta, they are for the most part the result of Tertiary eruptions, and have been modified by erosion to approximately the same extent in all cases. Superficially considered, — careful comparison being impossible at present, on account of the lack of observations,

— it would seem that the history of Mt. Shasta has been repeated, probably with many minor variations in each instance, at a number of localities along the Cascade range, and in its vicinity.

Crater Lake, Oregon.— One of the most remarkable of the extinct volcanoes of North America, known as Mt. Mazama, is situated in the Cascade Mountains, Oregon, thirty miles north of Klamath Lake, and is occupied by Crater lake. The mountain in which this lake is situated is thought to have been truncated by the melting and subsidence of its summit, which left a rudely circular cavity from five to six miles in diameter. The lake is 6239 feet above the sea, is 1975 feet deep and surrounded by nearly vertical walls ranging from 900 to 2200 feet high. The vast caldera is, then, about 4000 feet deep. The fact that the mountain has been truncated is shown especially by the character of the slopes that remain. These are scarred by radiating valleys of the same character as those on neighboring mountains which still preserve their conical forms, but open abruptly into the central caldera. The streams that flowed down these gorges, and to which their excavation is mainly due, have been *beheaded* by the falling in of the crater walls. The outer slopes of the truncated mountain also bear evidence of glaciation, showing that before the great catastrophe that removed its summit, it was ice-crowned and gave origin to radiating alpine glaciers of the same nature as those now to be seen on Mt. Shasta and Mt. Rainier, but descending to a lower level. Apparently the mountain has lost its summit since the Glacial epoch.

An account of Crater Lake, accompanied by references to the writings of C. E. Dutton, by whom it was made

known to geologists and geographers, is contained in a companion of the volume before you.[1]

Mt. Pitt.— In southern Oregon and about sixty miles north of Mt. Shasta rises a beautifully regular, volcanic cone known as Mt. Pitt. Although of secondary rank when compared with several more lofty summits in the Cascade region, yet its summit and sides are snow covered during the greater part of the year. As stated by Emmons,[2] there is a remnant of a crater at the summit, the walls of which are broken down, especially on the northeast side. The lavas that have been discharged from the crater, or from secondary openings on its sides, resemble, in general, those poured out at Mt. Shasta, but present certain peculiar features that promise interesting results when studied in the light of modern petrographic methods.

Three Sisters and Mt. Jefferson.— To the north of Mt. Pitt, — as stated in the instructive paper by Emmons, cited above, — and in the main line of the Cascade Mountains, the group of volcanic peaks termed the Three Sisters, and a neighboring cone, Mt. Jefferson, mark the sites of still other ancient volcanic lights. Little accurate information is available concerning these attractive mountains, except that they are of volcanic origin, although now

[1] I. C. Russell, "Lakes of North America," Ginn & Co., Boston, 1895, pp. 20, 21, and map.

A map of Crater Lake with descriptive text and illustrations has been published by the U. S. Geological Survey, with the title "Crater Lake Special Map." A highly instructive paper on Crater Lakes, by J. S. Diller, may be found in "The American Journal of Science" for March, 1897; and in a more popular form in the "National Geographic Magazine" for February, 1897.

[2] S. F. Emmons, "The Volcanoes of the United States Pacific Coast," in American Geographical Society, Bulletin No. 4, 1876–77, p. 40.

FIG. A. Mt. Hood, Oregon, looking east, April, 1895. (Photograph by Gifford and Hale, Portland.)

FIG. B. Fumarole in snow-filled crater of Mt. Hood, Oregon, July, 1894. (M. W. Gorman.)

cold and silent, and much modified by erosion. They form most beautiful features in the magnificent scenery of Oregon. Their tapering summits, when snow covered, present striking contrasts with the sombre green of the pine-clad mountains and hills with which they are surrounded. It is now known from exploration conducted by J. S. Diller, that glaciers of considerable size occupy sheltered valleys among the clustering summits of the Three Sisters.

Mt. Hood. — This majestic mountain, 11,225 feet high, is stated by Emmons to have the most graceful outlines of any of the justly famed volcanic peaks of the northwest coast. It rises from the very crest of the Cascade range, in northwestern Oregon, and about twenty-five miles south of the Columbia River. From the city of Portland, it forms the crowning summit of a far-reaching landscape. Something of the grandeur of this mountain, which bears a similar relation to Portland that Vesuvius does to Naples, may be gathered from the accompanying illustration (Plate 12, Fig. A). Its lower slopes, as is the case of all the lofty peaks in Oregon and Washington, are densely forested, and form an ideal setting for the dazzling cone rising above them. Could an observer obtain a bird's-eye view of the Cascade Mountains, they would appear as a belt of emerald studded at irregular intervals with immense brilliants.

When the English explorer, Vancouver, who gave Mt. Hood its name, first saw the mountain, he estimated its height to be at least 25,000 feet, and thought it was perhaps the highest summit in the world. Barometric and other measurements, however, made by the United States Coast Survey and by the Fortieth Parallel Survey, have

shown that Vancouver's estimate was more than twice the actual height. In spite of the corrections that prosaic measurements have imposed upon the fancy of distant observers, Mt. Hood, if not the most lofty, is, yet, in the eyes of its admirers, one of the most beautiful of mountains.

The summit of Mt. Hood, like many other similar peaks in the same region, retains only a portion of the walls of the original summit crater. It was ascended in 1888 by M. W. Gorman, a member of the mountain club (Mazamas) of Portland, who reports that there are still fumaroles on the northeast slope, and steaming rifts on the south side near what is known as Crater rock, at an elevation of about 8500 feet above the sea. The sulphurous fumes from these openings are sometimes so strong as to be overpowering, and will discolor silver at a distance, in the direction the wind is blowing, of half a mile from where they issue. One peculiar phenomenon, shown on Plate 12, Fig. B, is the occurrence of a fumarole in the deeply snow-filled crater. The actual summit of the mountain consists of a single block of lava only a few feet square, from which one may look down almost perpendicularly for thousands of feet on the north, and in other directions the descent into the forests far below is almost as precipitous. In the shelter of the peak on the north side, where the walls circle round what is stated to have once been a crater,[1] clouds frequently collect even on clear days, and from time to time rise above the peak so as to make it seem as if steam was still issuing from the summit. So deceptive is this appearance

[1] This great depression has certain features which suggest that it is an amphitheatre of glacial origin.

FIG. A. Mt. St. Helen's, Washington. (M. W. Gorman.)

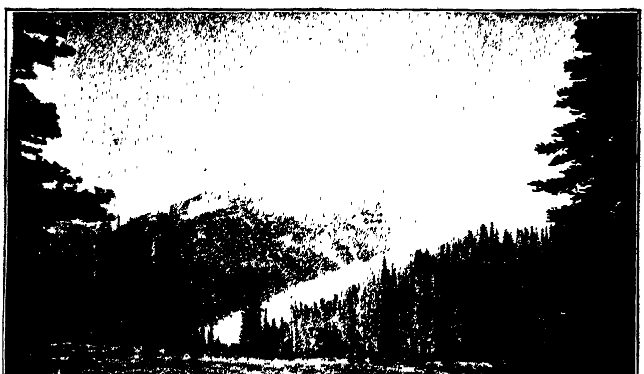


FIG. B. Mt. Rainier, Washington, from the south. (Photograph by Braas, Seattle.)

that reports are frequently made of an eruption. As shown by Arnold Hague, who has examined the summit, no eruptions have taken place within many years; and certainly not within the memory of man. To judge from a distant view, as well as from the reports of those who have trodden its dizzy heights, it is a typical example of a volcanic mountain that has passed its prime and is slowly yielding to destructive agencies of the atmosphere.

It is stated by George Gibbs[1] that stumps of trees occur in abundance on the side of Mt. Hood above the present timber line, suggesting that formerly the heat of the mountain was sufficient to encourage the growth of forests at an elevation which was impossible when the mountain became cold. That this is the true explanation of the former extent of timber growths seems doubtful, in view of the antiquity of the later eruptions as determined by careful observers who have examined the mountain.

Mt. Adams and Mt. St. Helen's. — About thirty miles north of the Columbia and sixty miles from Mt. Hood, stands Mt. Adams, one of several great mountains of which the people of Washington are justly proud.

Mt. Adams is seen to the greatest advantage from the eastward, as it stands well to the east of the crest of the Cascade range. Several fine views of its deeply truncated summit and of its scarred slopes were obtained by the writer while studying the geology of central Washington, in 1893. Its shape is that of the frustum of a cone. If its sides could be prolonged upward, they would meet at least a thousand feet above the present flat-topped summit. Whether the breadth of the summit is due to

[1] American Geographical Society, Transactions, Vol. IV, 1874, p. 353.

the great size of the original crater, to the blowing away of the top, or to some other cause, has not been determined. Although comparatively easy of ascent, it has not received the attention it deserves, and so far as I am aware, no competent observer has examined its summit.

On the west of the Cascade and like Mt. Adams, standing at a distance from the crest of that range, is another outpost of the mountains, known as Mt. St. Helen's. The country between these two peaks is rugged and heavily forested. Mt. St. Helen's (Plate 13, Fig. A), in contrast with its companion on the east, has a more regular conical form and is said to rise from all sides to a comparatively sharp apex. Photographs of the peak fail to show, however, that it is more regular or fresher in appearance than its companion. Its reported conical form suggests that it is younger than Mt. Adams, although, as mentioned above, the truncation of that mountain may be due to an explosion and not to weathering, in which case its general form would not be an index of advancing age.

If the statements of frontiersmen can be relied upon, Mt. St. Helen's is not only young, but has been in a state of activity within the past fifty years. Emmons says in his essay on the volcanoes of the Pacific coast, already referred to, that this mountain is the only one in the far Northwest concerning which he was able to obtain a definite account of a recent eruption. He was told by a French Canadian voyageur, that it was in active eruption during the winter of 1841–42. As stated by the gentleman referred to, the light from the volcano at the date mentioned was so intense that one could see to pick up a pin in the grass at midnight near his cabin, some twenty miles distant. Mr. Emmons did not visit the

mountain, but states that with the aid of a field-glass he could distinguish the apparent track of a lava flow which had cut its way through many miles of the forest that clothes the mountain's sides.

Mr. M. W. Gorman has informed me that he ascended Mt. St. Helen's in 1889, and found fumaroles on the north-east side, but no steaming crater, although, as he states, the volcano seems to have been active in recent years, and is fresher in appearance than Mt. Hood. Lava has flowed northward from the mountain for about twenty miles, in some places passing through a forest of Douglas fir, and at certain localities cooled about large trees so as to take a cast of their charred and seamed trunks. The trees have since disappeared, leaving well-like openings which still remain unfilled. Specimens of the lava-casts of the bark of one of the trees thus surrounded has been sent to me by Mr. Gorman, and is a most interesting specimen. He states also that in one place the lava dammed the end of a canyon and led to the formation of a lake which is still without an outlet. When the last eruption took place, the lava appears to have flowed over wet places and the steam generated, escaped at the surface, leaving what are termed "blow holes."

Mt. Rainier. — For many reasons Mt. Rainier is considered by admirers of the beauties of mountain scenery, the finest single peak in the United States, not including Alaska. The secret of its grandeur is not so much its exalted height, 14,525 feet, although it is the loftiest summit on the northwest coast, but its isolated position, and because it rises practically from sea level. It is one of the few mountains in which the visual height, or the part that rises above the observer, is from many

points of view nearly the same as the actual elevation of the summit above the sea. Mt. Rainier is in plain view from Puget Sound. From the city of Tacoma, its shining summit is wonderfully attractive (Plate 14). Other elements that combine to make Mt. Rainier both picturesque and sublime are the dense evergreen forests that cover the country about its base and extend far up its rugged side, the perennial snow that crowns its summit, and its fine glaciers which descend far into its encircling forest.

The first ascent of Mt. Rainier seems to have been made by Messrs. Hazard Stevens and P. B. Van Trump,[1] who after many hardships reached its summit in August, 1870. In October of the same year, Messrs. S. F. Emmons and A. D. Wilson of the United States Geological Exploration of the Fortieth Parallel, also made the ascent. The report of this highly successful expedition contains, so far as I am aware, about all the published observation concerning Mt. Rainier that are of value to the student of volcanoes.[2] A few selections from this interesting report will enable the reader to picture some of the salient features of the magnificent mountain which still awaits detailed exploration and careful study.

"Under the guidance of our Indians, a comparatively easy though rather moist march of a day and a half brought us finally on to the crest of the spur east of the Cowlitz River. As we gradually emerged from the forest region on to the more open ridge, where grew only isolated clumps of mountain fir and huckleberry bushes, the rain-

[1] "Atlantic Monthly," Vol. 38, 1876, pp. 513–530.

[2] S. F. Emmons, "The Volcanoes of the United States, Pacific coast," American Geographical Society, Bulletin No. 4, 1876–77, pp. 31–61.

clouds which had enclosed us for the past three days broke away, and disclosed another superb view of the mountain, now quite near us, and yet seemingly more lofty and inspiring than ever.

"The details of its surface were now visible. The very summit was marked by a thin horizontal black line which we later found to be the rim of the crater. Below this stretched a smooth unbroken envelope of white, apparently about a third of the way down; then, at irregular distances along its sides, peeped out black shoulders of rock between which were deep broken masses of glacier ice, looking like foaming cascades frozen in the instant of their fall. This lower two-thirds of the peak was the steepest of all, and below it the glaciers, taking the form of rivers, flowed out at more gentle angles, gradually hidden in their ever-deepening beds between the grassy spurs." A day or two later the summit was reached. "We stood upon the edge of a bowl-shaped crater of almost perfect circular form, forming the eastern edge and highest point of the mountain, its interior filled to within thirty or forty feet of the rim with ice and snow, while on its outer slopes the blackened lava, of which it is composed, was laid bare for a hundred feet or more below the summit. This was the delicate black line, which we had sometimes been able to distinguish from below, as forming the summit. Adjoining this on the west was another semicircular rim of rock, peeping out of the snow, the remains of a former crater, in the interior of which this more recent one had built itself. It was strange to see even these comparatively small patches of rock free from the universal covering of ice and snow; the explanation first presented to the mind was their exposed position,

and the tremendous force of the wind, which seemed almost sufficient to blow away the rocks. A second was soon seen in the evidence of internal heat at no great depth below the surface, shown by countless jets of steam and gas of size from a pinhead to an inch in diameter, issuing around the interior rim of the crater. Near these jets the hard rock is changed into a red clayey mass and in front of them, by the condensation of the steam, ice caverns have been formed, some of sufficient size to admit several persons. In one of these we took refuge for a few moments to warm ourselves and thaw our fingers, two of mine being slightly frozen. . . .

"From our summit we could see the two other peaks, only a few hundred feet lower than ourselves, the one to the southwest, and the other northwest, from one to two miles distant, and separated by the heads of a deep valley filled by névé ice, which sloped rapidly to the westward between the two peaks. It was evident that this valley was the interior of a still older and larger crater, of the walls of which these two peaks are the remnants. The crater upon which we stood had been built up as an interior cone entirely within the wall of this older crater, and the outstanding pinnacles of rock on the east, which we had observed on our first day's climb on the glaciers, must be the only remnant left of the east side of this outer cone; over a third of the mountain mass had been carried away and that largely by the energy of glacier ice.

"From the northeastern rim of the crater, we could look down on an unbroken slope of nearly 10,000 feet to the bed of White River, the upper half or two-thirds of which was so steep that one had the feeling of looking

Mt. Rainier, Washington, from near Tacoma, looking southeast, June 14, 1896. (Photograph by A. H. White, Tacoma.)

over a perpendicular wall. The system of glaciers, and the streams which flowed from them, lay spread out as on a map at our feet; radiating out in every direction from the central mass, they all with one accord crossed to the westward, to send their water down towards Puget Sound or the lower Columbia River.[1]

"Looking to the more distant country, the whole stretch of Puget Sound, seeming like a pretty little lake embowered in green, could be seen in the northwest, beyond which the Olympic Mountains extended out into the Pacific Ocean. The Cascade Mountains, lying dwarfed at our feet, could be traced northward into British Columbia, and southward into Oregon, while above them, at comparatively regular intervals, rose the ghost-like forms of our companion volcanoes. To the eastward the eye ranged for hundreds of miles over chain on chain of mountain ridges, which gradually disappeared in the dim blue distance."

Mt. Baker. — The most northerly of the volcanic piles connected with the Cascade Mountains south of the United States-Canadian boundary is Mt. Baker. What the characteristics of the north extension of this volcanic belt may be, remains to be discovered, but at present no recent volcanoes are known in the region immediately to the north of the international boundary.

Concerning Mt. Baker, little can be said. It rises from the dense forest that extends from the Pacific coast east-

[1] An account of these glaciers may be found in "Glaciers of North America" by I. C. Russell. Ginn & Co., Boston, 1895. pp. 62–67.

The writer ascended Mt. Rainier in the summer of 1896, and passed a night in one of the craters at the summit. A report on the glaciers visited will be published in the 18th Annual Report of the U. S. Geological Survey. A popular account of the expedition will appear in "Scribner's Magazine."

ward to beyond the Cascade Mountains, and is fully twenty-five miles west of the crest of the main range. From Puget Sound it is in full view on clear days and appears as a conical peak which from its form is at once seen to be of volcanic origin. From the north and east especially its summit appears to be truncated. Whether this is due to erosion or to volcanic explosion has not been determined.

Gibbs[1] states that he was informed by officers of the Hudson Bay company and also by Indians, that Mt. Baker was in eruption in 1843, and that "it broke out simultaneously with Mt. St. Helen's, and covered the whole country with ashes." It was reported that during this eruption, a neighboring river, the Skagit, was obstructed and all the fish in it died, and also that "the country was on fire for miles around." The truth of these reports is to be taken with some reserve, however, since a fire on the mountain might be mistaken by unskilled observers for a volcanic eruption.

The Cascade Mountains

The Cascade Mountains extend from northern California northward, with a nearly north and south trend, across Oregon and Washington. At the south, the range terminates in the Lassen peak volcanic district, already briefly described; its northern extremity has not been definitely ascertained, but is probably not far north of Mt. Baker. In round numbers, the length of the range is 500 miles, and its average width about fifty miles. In general, it is

[1] George Gibbs, "Physical Geography of the Northwestern Boundary of the United States," American Geographical Society, Journal, Vol. IV, 1873, p. 358.

parallel with the coast line of the Pacific, 120 miles distant from the crest of the range at the south, and 200 miles at the north. The crest line, although irregular in height, is in general from 5000 to 8000 feet above the sea, and is broken by several passes, more especially in the northern half. The deepest gorge, and the only one which permits the drainage of the interior to cross the uplift to the Pacific, is that through which Columbia River flows.

It is frequently stated or implied, that the Cascade Mountains are composed mainly of lava, and that the range owes its prominence to the accumulation of successive sheets of this material, which have flowed from vents near the crest of the range, and cooled and hardened so as to build up a great ridge. If my understanding of this hypothesis is correct, the Cascade range is considered to have originated in much the same way as certain isolated volcanic mountains, like those of the Hawaiian islands for example, in which successive overflows of molten rock have been piled one above another. Under the hypothesis referred to, one is led to infer that many mountains of the Hawaiian type have been formed along a line of fissures, and that their lava sheets interlaced so as to form a much elongated ridge. It has been stated, also, that the Cascade Mountains differ from the Sierra Nevada, in that the former have the general structure just mentioned, while the latter owes its leading features to the uplifting and tilting of long, narrow blocks of the earth's crust adjacent to faults.

Although the structure of the Cascade Mountains has not been systematically studied, and any positive conclusions in reference to the mode of origin of the range

would be premature, yet there are several facts known which are inconsistent with the hypothesis just stated and point to another explanation.

During two expeditions conducted by the present writer in the region adjacent to the Cascade Mountains on the east, one in Oregon and the other in Washington, the eastern border of the range was examined. The monoclinal structure so characteristic of the western portion of the region, known as the Great Plain of the Columbia, and of its southern extension in the Great Basin, due to the tilting of fault-blocks, was found to extend to the mountains on the west. As one approaches the Cascade range from the east, the tilted blocks, the upturned edges of which are short mountain ridges, become of larger size, and form the immediate foothills of the main range. This merging of the structure characteristic of the interior basin with the mountains bordering it on the west, so far as my own observations extend, is more pronounced in central Washington than elsewhere.

From what I have seen of the Cascade Mountains I venture to suggest as a working hypothesis, that the lava composing them, more especially to the south of Lake Chelan in Washington, is an extension of the Columbia lava — described a few pages in advance — which covers such a vast area in the eastern portion of Oregon and Washington. This lava was poured out in successive sheets and afterward broken over extensive areas, by fractures, and the blocks thus formed tilted at various angles. The hypothesis here suggested assumes that the Columbia lava extended over the Cascade region in originally horizontal sheets, and was, subsequently, broken and

tilted. The structure of the Cascade Mountains, under this hypothesis, is therefore not different in its main features from that of the Sierra Nevada.

The Cascade Mountains are not composed wholly of lava, as seems to be the prevailing idea, derived apparently from reconnoissance in their southern portion. Beneath the lava in central Washington, there are Tertiary rocks, and highly metamorphosed beds of unknown age. These basement rocks share in the disturbances that have affected the lavas resting on them. Much of the northern portion of the range is free from lava, and differs in a marked way in all its scenic features from the heavily lava-covered portion to the south. In the northern portion, the rocks are largely granite and schist, showing at once that to ascribe a volcanic origin to the range, as a whole, is inadmissible.

The great volcanic peaks described in the past few pages are of later date than the uplifting of the main Cascade range, and probably owe their origin to the escape of molten material through fractures formed at the time the mountain blocks were separated one from another by fractures, and severally upraised.

Of the two hypotheses that the reader now has before him, the first, namely, the one which refers the origin of the Cascades to volcanic overflows, finds its greatest support in the southern portion of the range; while the second, or the one that seeks to explain the main topographic features of the mountains by fracture and upheaval, applies more particularly to the central and northern portions of the same mountain belt. When the Cascade Mountains have been thoroughly explored, it may possibly be found that each of these hypotheses is

in part correct, and that the range is less simple in structure than is now supposed.

Columbia Lava

Merging with the Cascade Mountains on the east and extending through Washington and Oregon, far into Idaho, there is a vast lava-covered country, which is without prominent points of eruption. In fact, cinder and lapilli cones of any description are almost entirely absent. The boundaries of this lava-covered region have never been traced except for a few score miles in north-central and eastern Washington, but it is estimated to have an area of from 200,000 to 250,000 square miles. The region most nearly comparable with it is in India, previously referred to, where the Deccan trap covers approximately the same area. These two great basaltic areas have also many points in common in reference to the character of the rocks composing them, the manner in which the lava occurs in sheets interstratified with lacustral sediment, etc. The Deccan trap is thought to be of Cretaceous, while the Columbia lava is of Tertiary age.

The Columbia lava is not one vast flow, but is composed of many independent sheets, which are sometimes separated by land surfaces containing the stumps of trees and even huge trunks buried in lapilli and now thoroughly silicified. The lava sheets overlap and supplement one another so as to form a continuous and highly compound system. No single sheet can be traced over the entire field, but yet in the sides of the numerous deep canyons that have been eroded in the lava, individual flows can frequently be followed for a score or more of miles. The

series varies in thickness from a few score feet at certain localities on its borders, to over 4000 feet in southeastern Washington, where it has been deeply dissected by Snake River, without, however, revealing its maximum vertical extent. In the walls of the canyon cut by the Columbia, according to Le Conte,[1] the aggregate thickness of the many lava sheets exposed is 3700 feet. Its average thickness is thought by Symons[2] to be not far from 2000 feet. My own observations suggest that this estimate is too low, but no conclusion of much value in this connection can be reached until more extensive surveys have been made.

Many sections of the Columbia lava were seen by me in Washington and Oregon, the most instructive being along the Columbia and Snake rivers and some of their tributaries in Washington. The rock is usually a black basalt, with frequently a well-defined columnar structure, but at times is also highly vesicular and scoriaceous, especially on the surface of the sheets. Many times the marked columnar structure recalls the finest of the basaltic columns so well known at the Giant's Causeway and on the Isle of Staffa. The walls of the canyon cut in the lava are similar to the Palisades of the Hudson, but are far more extensive and usually exhibit several distinct colonnades one above another, which can be followed for scores of miles.

As previously stated, there is a general absence of cones of eruption throughout the region covered by the Columbia lava. In view of the original extent of the lava

[1] "American Journal of Science," Vol. 7, 3d series, 1874, p. 168.

[2] "Report of an Examination of the Upper Columbia River," Washington, 1882, 47th Congress, 12th Session, Ex. Doc. No. 186, p. 100.

westward, mentioned above, namely, that it includes the region of the Cascade Mountains; the great volcanic peaks like Shasta, Rainier, etc., must be considered as points of eruption from which some of the lava flows originated. The flows from these craters, however, are comparatively small in volume, did not spread widely, and in part are of more recent origin than the main body of the lava sheets with which they are associated.

The absence of cinder cones, lapilli craters, etc., over all of the region covered by the Columbia lava east of the Cascade Mountains, from which the great lava sheets could have been derived, has led to the conclusion, first suggested, I believe, by Roichthofer, that the lava came to the surface through fissures, in a highly fluid condition and spread widely over the country without forming volcanic mountains. This conclusion is sustained by observation made by me on the eroded edge of the Columbia lava, about twenty miles west of Ellensburg, Washington, where the border of the lava has been removed and a deep valley formed, the eastern wall of which is capped by the lava, which rests unconformably on sandstone and shales. In the sedimentary rocks beneath the lava cap, there are large dikes that lead up to and merge with the lava forming the surface. These dikes show that the surface lava, in part at least, came through large fissures and spread out in sheets over the land.

Near the upper surface of the Columbia lava in central Washington, near Yakima, there is a thin layer of clay formed as a sediment in a Tertiary lake and subsequently covered by a lava flow a hundred feet thick. Above this bed of basalt and resting evenly on its surface are gravels and fine, evenly bedded lacustral sediments, having a

thickness of 125 feet; next above is an interstratified sheet of columnar basalt, varying from 40 to 100 feet in thickness, which may be traced in an east and west direction for 75 to 100 miles. Above this widely spread sheet are lacustral sediments known as the John Day system, which in places is rich in the remains of large mammals, showing it to be of Tertiary age.

Many sections of the lava and of interstratified lacustral sediments, show that a period marked by great volcanic overflows ended in a lacustral period during which an extensive region to the east of the Cascade Mountains was occupied by a great lake, or perhaps a series of large lakes of Miocene age, in which hundreds of feet of fine sediments were deposited. These records furnish evidence that the main inundations of lava occurred somewhere near the middle of the Tertiary period, and not during the Glacial epoch, as some writers have supposed. That the lava is of older date than the Glacial epoch is also shown by the fact that in places its surface has been smoothed and striated by moving ice and is covered with moraines. The lava does not form a vast unbroken surface, but, especially in central Washington and in central Oregon, has been disturbed by orographic movements and deeply dissected by streams since the last addition of molten rock was made to the series. These changes in topography increase in extent as one travels westward from the eastern margin of the lava-covered country and culminate in the Cascade Mountains.

In southeastern Washington the Columbia lava has been but slightly disturbed over an area of several thousand square miles, and furnishes an example of the leading characteristics of the vast lava-covered region of which it

is a part, after the final outpouring of molten rock and before the beds were fractured and upheaved. The level surface of the basaltic plateau meets the mountains of older rock in much the same manner that the ocean joins a rugged and deeply indented coast. The molten lava entered the valleys and gave them level floors of basalt; the deeply sculptured ridges between the valleys were transformed into capes and headlands; outstanding mountain peaks became islands in the sea of molten rock. One of these island-like mountain peaks, known as Steptoe butte rises 1000 feet above the surrounding plateau and is about twelve miles distant from the shore of the once fiery sea. Snake River flows across the basaltic plateau and has excavated a magnificent canyon some 4000 feet deep and fifteen miles broad. Within the canyon there are numerous lateral ridges and a multitude of striking architectural forms due to erosion. The excavation of the canyon has revealed the summits of angular mountain ranges that were surrounded and finally buried by the successive inundations of molten rock. One of these buried peaks rises about 2500 feet above the river and is covered by fully 1500 feet of horizontally bedded basalt. These are but a few of the facts that have been observed which demonstrate the extent and character of the vast fissure eruptions that occurred from time to time during tens of thousands of years in the far northwest.

The surface of the Columbia lava is covered with deep, rich, residual soil which has resulted from the slow disintegration and decay of the basalt, and furnishes the marvellously productive wheat-lands for which Oregon and Washington are justly celebrated. In autumn the boundless plateau is a golden sea of waving grain.

The conditions presented on the eastern border of the Columbia lava in Idaho, are thus described by Geikie:[1] "We found that the older trachytic lavas of the hills had been deeply trenched by lateral valleys and that these valleys had a floor of the black basalt that had been poured out as the last of the molten materials from the now extinct volcanoes. There were no visible cones or vents from which these floods of basalt could have proceeded. We rode for hours by the margins of a vast plain of basalt, stretching southward and westward as far as the eye could reach. It seemed as if the plain had been once a great lake or sea of molten rock which surged along the base of the hills, entering every valley, and leaving there a solid floor of bare black stone."

Westward the general conditions observed by Geikie extend through Idaho, Oregon, and Washington, but the westward flowing streams, and particularly Snake River, have made deep channels in the lava, so that crossing it in a straight line is impossible.

On the Great Plains of the Columbia in central Washington, there are many deep canyons termed *coulées* which have been eroded by streams, along lines of faulting. The most remarkable of these, and one of the most noticeable topographic features of the region, is what is known as the Grand Coulée.[2] This is a trench across the lava with vertical walls from 300 to 400 feet high, between which there is a flat-bottomed valley, from a mile and a half to four miles broad, occupied in part by

[1] Archibald Geikie, "Geological Sketches at Home and Abroad, 1882," pp. 337, 338.

[2] The word *coulée* is used in the far Northwest to designate a steep-sided valley or what in more southern states and territories would be designated as canyons. *Coulée* is also used to designate a lava flow.

lakes, some of which are without outlets and strongly alkaline. Its length from the Columbia River at the north to Coulée City is about thirty miles; its eastern wall then disappears and the level floor of the canyon merges with the plain which extends eastward; the western wall is continued for twenty miles farther and overlooks a narrow but still wilder and more desolate valley than that of the Grand Coulée itself, which is bounded on the east by another vertical wall that begins just south of Coulée City. The top of the east wall of the canyon to the south of Coulée City is on a level with the bottom of the gorges to the north; the descent from one portion of the coulée to the other is vertical, and over this rugged escarpment formerly rolled a river comparable with the Niagara.

The great coulée (canyon) briefly described above, like many others of a similar nature, although of smaller dimensions, in the same region, is due primarily to a faulting of the lava, and the enlargement of the break thus formed by river erosion. Central Washington is now an arid region in which no perennial streams of any considerable magnitude originate. Snake River flows across this region in a deep canyon, and derives its water supply from the mountains of Idaho. Formerly, however, the climate was more humid than at present, and many streams flowed through what are now dry and desolate valleys. During the Glacial epoch the Columbia in the northern portion of the great curve it makes about the northern border of the Columbia lava, was blocked by a glacier that flowed from the north; the rise was thus held in check and escaped southward along the Great Coulée, and plunging over the escarpment in its course near the

present site of Coulée City formed a magnificent cataract.[1]

Volcanoes of the Coast Range

At only a few points in the Coast Mountains immediately bordering the Pacific in the United States, from the Olympic Mountains at the north to the Mexican boundary, are there volcanic rocks of recent origin. As the few extinct volcanoes that we know in this region furnish no features not already well illustrated by the examples previously considered, we can pass them by for the present with but a word.

Dana[2] has described an extinct volcano known as Saddle Mountain, in Oregon, about fifteen miles south of the Columbia. This is a crater now extinct and forest covered, that is about two miles wide and approximately 500 feet deep.

Muir's butte in California, south of San Francisco Bay, is another prominent volcanic pile, which has been much eroded but still retains the gracefully curving slopes so characteristic of cinder cones.

Volcanoes of the Rocky Mountains

Although igneous rocks are abundant throughout the greater portion of the belt of rugged country known as the Rocky Mountains, but a few volcanoes occur there

[1] An account of the Big Bend country in Washington, and of the west central portion of the region crossed by the Columbia lava may be found in "A Geological Reconnoissance in Central Washington," by I. C. Russell, U. S. Geological Survey, Bulletin No. 108. Reference to previous publications on the same region are there given.

See also, I. C. Russell, "Reports on a Geological Reconnoissance in Southeastern Washington," U. S. Geological Survey. *In press.*

[2] J. D. Dana, Reports of the Wilkes Expedition, "Geology," 1849, p. 644.

which are sufficiently recent to retain their characteristic topographic forms. Much may be learned in this region, however, respecting the internal structure of volcanic mountains, and of the nature of their originally deeply seated roots, as they may be termed, for the reason that erosion has in many instances dissected these ancient piles and laid bare their anatomy.

Blackfoot Basin, Idaho. — In southeastern Idaho there are at least two or three small basaltic craters which still retain their characteristic shapes and are probably closely associated in time with the outflows of the adjacent Columbian lava. As described by A. C. Peale,[1] one of these craters is a circular depression 130 yards in diameter and ten to twenty feet deep. Surrounding it is a rim of variously colored scoriaceous basalt fifty feet broad on its crest. The crater is of the nature of a parasitic cone, possibly originating from lava flowing over water, and is surrounded by a lava field. About ten miles distant is another similar crater, but not so regular and less well preserved. Other poorly defined craters, together with vesicular basalt and fine lapilli, are mentioned as occurring in the same region.

Colorado. — The evidence of late volcanic eruptions in Colorado is summarized by F. M. Endlich[2] as follows, but the weight of evidence seems to assign the greater part of the eruptions mentioned to Tertiary time:

"A number of isolated basaltic eruptions occur in Colorado. Prominent among them is that of Golden City, where there are table mountains composed of lig-

[1] Eleventh Annual Report of the U. S. Geological and Geographical Survey of the Territories (F. V. Hayden in charge), 1877, pp. 561, 562.

[2] Tenth Annual Report of the U. S. Geological and Geographical Survey of the Territories (F. V. Hayden in charge), 1878, pp. 250, 251.

nitic beds covered with basalt. M. Marvine says with regard thereto: 'The source of this lava is from beneath North Table Mountain, on the summit of which, and near the northwest corner, the remnants of a group of small volcanic cones may still be seen; weather-beaten and nearly worn away, they still suffice to show from whence the lava came.' This explains, in a few words, both the source of the basalt and the character of such eruptions. Not far from Golden, at Valmont, a heavy dike of the same material may be observed. Inasmuch as we may safely regard isolated eruptions as the results of local dikes that have overflowed, that of Valmont deserves mention here.' Two small basaltic cones near Canyon City are also mentioned. These have since been examined by the present writer and found to be much wasted cinder cones, which have lost the depressions that probably once existed in their summits. Worn and eroded as they are, they appear to be among the most recent eruptions to the east of the main Rocky Mountain uplift. A few other occurrences of basalt in Colorado are mentioned by Endlich in the report just cited, and in conclusion he says: "Although the basaltic eruptions have been productive of forms resembling crater cones more closely than any of the other eruptions, not one occurrence has been observed in Colorado that could directly be compared to the cone and crater of an active or typical volcano."

Spanish Peaks. — To the student of volcanoes, the most interesting mountains in Colorado are the Spanish peaks, situated in the southeastern part of the state, about sixty miles south of Pueblo. There are two prominent peaks in the group referred to, which rise 12,720 and 13,620 feet, respectively, above the sea, — the adjacent valley

has an elevation of about 5000 feet, — and present fine examples of the ruins of ancient volcanoes. These two peaks rise abruptly from a region of comparatively mild relief and on account of their isolated position are impressive from whatever direction they are seen, not only on account of their height, but because of their sculpturing and varied colors. They are sharp, conical peaks from which radiate a large number of narrow, wall-like ridges formed by dikes, which mark the courses of fissures. These dikes, now weathered out so as to stand in bold relief, extend from the plain up the mountains to their very summits. Neighboring volcanic tablelands give evidence that still other dikes and sheets of igneous material have crumbled away, leaving only isolated remnants. East Spanish peak is lower than its companion and also presents steeper outlines, more sharply cut slopes and ridges, but less of the characteristic dike-walls, than its neighbor. The main body of this beautiful mountain is composed of red sandstone that has been altered by heat, so as to produce a number of species of metamorphic rocks. On ascending the western peak from the south, one passes over red sandstone, until near the timber line (10,000 feet), where large masses of igneous rock are encountered. As described by Endlich:[1] "Fragments of numerous varieties of trachyte and rhyolitic trachyte lay scattered about at the base of the mountain in great profusion. Vertical places are seen along the ridge we propose to climb, and on reaching them we find that they are caused by dikes. There are from two to sixty feet in thickness and not infrequently extend from near the

[1] F. M. Endlich, Ninth Annual Report, U. S. Geological and Geographical Survey of the Territories (F. V. Hayden in charge), 1875, pp. 129, 133–136.

summit down into the valley for several miles. All the strata in their immediate neighborhood have been baked, and much metamorphosed. Near the top of the mountain the sedimentary beds have totally disappeared and nothing remains but the trachyte brilliant with brown mica, white oligoclase, and long, shining needles of black hornblende. This cap of igneous rock rests on the sedimentary beds and, together with the numerous radiating dikes and the hardening of the sedimentary layers by heat and heated solutions, has preserved them from erosion."

Evidently the highest summit of the Spanish peak is a remnant left by erosion. The ancient volcano has been completely removed. Only its roots remain. The west peak contains more trachyte than its neighbor, but this rock also rests on sandstone, and sends out a number of radiating dikes, which descend to the adjacent plain as conspicuous ridges.

Some of the ridges radiating from the Spanish peaks show a remarkably straight course, while others follow irregular lines. Owing to the removal of the sedimentary beds that once enclosed the dikes, the intruded rocks stand out in bold relief and can only be compared to cyclopean walls. Two of these are specially mentioned by Endlich which are eight and ten miles in length, respectively, with vertical sides, several hundred feet high. In some instances the hardened sedimentary beds adjacent to the dikes also resist erosion, and each side of the central wall of igneous rock is flanked by a somewhat gentle slope composed of sedimentary beds.

Transverse dikes also exist which cross those radiating from the central peaks at acute angles. Ramifications also occur in several instances; the branches retaining

the same size, however, as the dikes from which they diverge. Wherever creeks cross the protruding dikes, the ridges are broken through, but in no instance have they caused a deflection of the lines of drainage. More than fifty of the great dikes have been mapped, but there are many more that are not prominent topographic features and have escaped notice. Much more interesting and instructive information concerning the remarkable dikes is contained in the report cited above. In that report (page 135), 300 or 400 feet is given as an estimate of the amount of degradation over a large area, as shown by the prominence of the dikes that now form such a remarkable feature of the region. Students of erosion will now, I think, agree that these figures should be greatly increased. It seems to the present writer, from a study of the region adjacent to the Spanish peaks, as well as from the descriptions just cited, that 5000 or 6000 feet would be a small measure of the amount of surface material that has been carried away. The Spanish peaks have not only been reduced to the condition of volcanic necks, like those of the Mt. Taylor region, New Mexico, described on a previous page, but erosion has been continued until the necks themselves have been removed, and the very roots of the volcano to which they lead laid bare.

New Mexico. — The igneous rocks, which on account of their influence on erosion form marked features in the relief of southeastern Colorado, extend southward into New Mexico, and there become even more conspicuous. Many tablelands and isolated hills, or buttes, in New Mexico, owe their existence to summit layers of lava, which have sheltered and protected the sedimentary rocks beneath.

One of the most conspicuous of the elevated tablelands is the Raton mesa, situated in part in Colorado and in part in New Mexico. This nearly flat-topped table rises fully 1000 feet above the adjacent valleys, and is capped by a layer of basalt, which breaks away at the margins in vertical escarpments, owing to its columnar structure and the slow removal of the soft shale beneath. Southeast of Raton mesa are other similar but far more extensive tables, capped with what was formerly an extension of the same lava sheet. The lava is a portion of a widely extended layer, which at the time of its extrusion sought the lowest depression in the surface over which it flowed. From being the flooring of a valley, it has, by the lowering of the country about it, been left in bold relief. Other examples of the process by which valleys are transformed into buttes, mesas, and mountains attract the eyes of the traveller in many portions of the region here considered.

One of the few moderately recent volcanoes in northeastern New Mexico that have been described, is Ocaté crater, situated about thirteen miles north of Fort Union. This peak was climbed by Professor J. J. Stevenson and the writer in 1878, and found to be a moderately well-preserved crater of basaltic rock. It is a truncated cone, with slopes of not far from 20°. Its symmetry has been destroyed on the west side by an overflow of lava, and on the south the rim of the crater has been breached by erosion. The cone is bare of vegetation, with the exception of scattered tufts of grass. Loose fragments of lava are strewn over its sides. The surface within the crater is covered with scoriaceous lava, but the rocks in the walls show much variation in text-

ure and color. A lava stream from this crater, still clearly traceable, flowed a distance of five or six miles.

Ocaté crater stands on a broad plain free of basaltic lava, known in part as the Ocaté mesa, which is similar to Raton and neighboring tablelands to the eastward, and is thought by Stevenson to be of older date than the later eruptions of the crater.

Another extinct volcano was discovered by Stevenson about seven miles east of Fort Union, and wholly detached from the lava forming the Ocaté mesa. This crater is even better preserved than the one just described. Its typical conical form is well displayed and its rim is broken only by a narrow gap on its north side. The predominant rock is a hard, steel-gray basalt. The lavas from this crater, which is without a special name, flowed northward across the plain to where Mora Creek had previously cut a deep canyon. The lava entered the gorge and flowed as a narrow stream of molten rock between its precipitous walls. This flow occurred at a time when Mora canyon had been eroded to a depth of 860 feet below the top of its present walls. The molten basalt poured down, filling the chasm to a depth of 400 feet, and entered the still larger canyon of Canadian River, to which Mora Creek is tributary, and extended into it for a distance of three miles. Since the lava cooled and hardened, forming a dense resistant bed of basalt, the river has re-excavated a channel through it, and sunken to a depth of 230 feet into the rock beneath. Some idea of the time required for the work can perhaps be appreciated, when it is stated that the task performed is many times greater than that accomplished by Niagara River in excavating the gorge below the falls.

The lava in the canyon of the Canadian formed a dam which held the water in check and gave origin to a lake. On account of the lack of sediment in the water flowing from the lake, the erosion of the lava must have been exceedingly slow, until the basin above was filled. The time required for Niagara to cut its gorge cannot be determined with even an approach to accuracy, but has been variously estimated at from 7000 to 35,000 years. The task performed by the Canadian is much greater than the one Niagara has accomplished and the river is far less in magnitude. There are no facts available for estimating the age of the gorge in years, but in comparison with Niagara it is safe to say that 150,000 to 200,000 years have passed since the lava plunged in a fiery flood into the gorge of the Canadian.

As the crater from which this lava came is still well preserved, its rim being broken in only one place, it is evident that a vast lapse of time must have intervened since neighboring volcanoes, like those that have been dissected to form the present Spanish peaks, for example, were in existence. The study of topographic forms thus enables one to appreciate, even more vividly than the study of fossil organic remains, the vast periods of time embraced in geological history.[1]

From a general knowledge of the geology of New Mexico, gained by the writer from travel and from the reports of various geological reconnoissances that have been carried on there, it is evident that much of interest to the student of volcanic phenomena will be found when

[1] The craters briefly mentioned above, and the great volcanic mesas of the same region, have been described by Professor J. J. Stevenson, Vol. III, Supplement, "Geology," of the Report of the U. S. Geographical Survey West of the 100th Meridian (G. M. Wheeler in charge), Washington, 1881, pp. 167–172.

careful surveys shall have been made. The many features of interest in the region studied by Stevenson form but a beginning of what may be expected in the future, but at present we shall have to leave this exceedingly instructive region, as accurate information concerning it is not available.

Canada. — Respecting the occurrence of recent volcanoes in Canada, I am unable to give the student much assistance, owing to lack of recorded information. It is scarcely to be expected that the volcanic belt, 1000 miles broad in the United States, ends abruptly at the international boundary, and begins again in Alaska, but the reports of surveys that have been made in this intermediate country contain but meagre accounts of recent volcanic phenomena. The great source of information concerning the geography and geology of the vast region embraced in the Dominion of Canada, is the reports of the admirable Geological and Geographical Survey of Canada, issued at Ottawa.

North of the region occupied by Columbia lava, described on a former page, there are vast areas drained by Frazer River, which are covered with similar sheets of basalt and in many ways repeat the conditions observed in the region drained by the Columbia River. Future exploration may possibly show that there is a great northward extension of the Columbia lava, but so far as can be judged, the Frazer River area seems to be distinct. The lavas in this region rest on and are interstratified with Tertiary lake beds, and with beds of lapilli and volcanic dust; their surfaces are glaciated and moraine-covered, thus showing that in a general way at least they are of the same age as the Columbia

lava. The lava occur in sheets which collectively occupy an area of several thousand square miles, but their boundaries have never been surveyed. In describing the Frazer River region, Dawson states that no distinct traces of volcanic craters were observed, although important centres of extrusion are described.[1] No reports are known of volcanic eruptions in Canada within historic times.

Volcanoes of Alaska

In Alaska, and especially on the Aleutian islands, active and recently extinct volcanoes are so numerous that an attempt to give a detailed record of the various reports concerning them that have been made would lead to confusion. Most of the observations available are of what may be termed a qualitative character, for the reason that none of the volcanoes have been studied and no detailed report concerning them has been made. One of the most interesting volcanic regions in the world there awaits exploration.

Distribution. — All the active volcanoes of Alaska are on its southern border, and with but few exceptions are situated close to the sea on the Alaskan peninsula and Aleutian islands. The same is also true, so far as known, of the recently extinct volcanoes, with the exception of a number of small basaltic cones on the coast of Bering Sea near St. Michael, about seventy miles north of the mouth of the Yukon. So much of Alaska is yet unexplored, however, that any statement concerning the absence of extinct craters in the interior must be received with proper qualifications.

[1] G. M. Dawson, "Report on Explorations in British Columbia," in Report of Progress, Geological Survey of Canada, 1876–77, pp. 26, 75–83.

Southeastern Alaska, embracing a great number of islands that fringe the coast south of the latitude of Mt. St. Elias, is believed to be almost entirely free of volcanic cones, with the notable exception of Mt. Edgecumbe, situated on an island in the vicinity of Sitka. This is reported to be a basaltic crater, 2855 feet high, and to have been in action in 1796, the only time in history.[1] Mt. Calder and other peaks on Prince of Wales Island are reported to have been active in 1775. How much reliance is to be placed on these reports, however, which have been handed down from early Russian occupation, it is difficult to judge, especially as no reliable descriptions of the mountains mentioned has been made.

Mt. St. Elias, frequently stated to be a volcano and to have emitted steam at various times, is, as ascertained by me during two separate visits, not of volcanic origin. Mt. Fairweather resembles Mt. St. Elias so closely in outline that it seems safe to assume that it also is non-volcanic. There are no definite observations to show the presence of volcanic mountains between Glacier Bay and Mt. St. Elias, and from distant views of that region, coupled with actual study of the country for 60 miles to the west of Yakutat Bay, I judge that no volcanoes exist on that portion of the Alaskan coast.[2]

The Aleutian Volcanic Belt. — The conspicuous and in fact the only well-characterized volcanic belt in Alaska begins at the east, at the head of Cook's Inlet, and extends westward throughout the Alaska peninsula and Aleutian islands. This belt of igneous activity is nearly 1600

[1] W. H. Dall, "Alaska and its Resources," Boston, 1870, p. 467.

[2] "Second Expedition to Mt. St. Elias, Alaska," U. S. Geological Survey, 13th Annual Report, 1891–92, pp. 1–91.

miles long, with a width in general of less than forty miles. It is so narrow and well defined that two parallel lines drawn on a map of Alaska, twenty-five miles apart, may be made to include nearly every volcano in the belt that is known to have been active in historic times. This may, for convenience, be termed the *Aleutian volcanic belt.*

The numerous volcanic vents that mark the course of this long, narrow belt; the many earthquakes that have been felt at intervals since the discovery of Alaska in its vicinity; and many changes of level recorded by terraces as well as by the observations of white men,—all indicate that a fracture or perhaps a series of intersecting breaks in the earth's crust there exists, along which marked changes have taken place in recent times and are probably still in progress. The sea to the south of the Aleutian islands is deep. The deepest soundings obtained previous to 1896 were in that region, in what is known as the Tuscarora deep. North of the Aleutian islands lies Bering Sea, for the most part shallow, which corresponds with the submerged continental border along the Atlantic coast of North America. The conditions are such as to favor the view that the Aleutian volcanic belt is not only a belt of fracture, but that differential movements of the rocks of a pronounced character, on the two sides of the belt, have occurred; that is, it is a belt of faulting. The great faults in the Mt. St. Elias region will, perhaps, when traced westward, be found to merge with the fractures that have determined the course of the Alaska peninsula and Aleutian islands.

An outlier of the Aleutian volcanic belt to the eastward is Mt. Wrangell, on Copper River, 200 miles northeastward of the head of Cook's Inlet. This is a lofty volcano,

the height of which has never been accurately determined. Mt. Wrangell is said to have been in eruption in 1819; and at the time of the most recent reports from that region, was still sending out a column of steam from its summit. Several lofty peaks in its vicinity are probably also of volcanic origin, but this has not been definitely determined.

It is stated by Grewingk[1] that there is definite information of volcanic activity on twenty-five of the Aleutian islands. On these islands, forty-eight craters have been enumerated. In addition to these, there are at least four on the Alaskan peninsula, two on the shore of Cook's Inlet, one on Prince William Sound, and at least one — Mt. Wrangell — on Copper River, making, together with Mt. Edgecumbe and Mt. Calder, fifty-seven active or recently extinct craters. This number will, no doubt, be increased when detailed explanations are carried out.

Summaries of various reports, made largely by Russian explorers, concerning volcanic eruptions, earthquakes, hot springs, etc., in Alaska have been given by Dall,[2] Grewingk,[3] and Petroff[4]; the writings of these explorers, with the exception of Grewingk's travels, are easily accessible.

Cook's Inlet. — The west coast of Cook's Inlet rises

[1] Cited by Ivan Petroff in Report of Tenth Census, Washington, 1884, pp. 93–96.

[2] W. H. Dall, "Alaska and its Resources," Boston, 1870, pp. 286–290, 466–470.

[3] C. Grewingk, "Beitrag zur Kenntniss der orographischen und geognostischen Beschaffenheit der nord-west-küste Amerikas, mit den anliegenden Inseln," Mineralogical Society of St. Petersburg, Proceedings, 1850.

[4] Ivan Petroff, "Report on the Population, Industries, and Resources of Alaska"; in Reports of the Tenth Census, and of the Eleventh Census, Washington, 1884 and 1893.

FIG. A. Pavloff, Alaskan Peninsula. (Photograph by Lieut. A. L. Broadbent.)

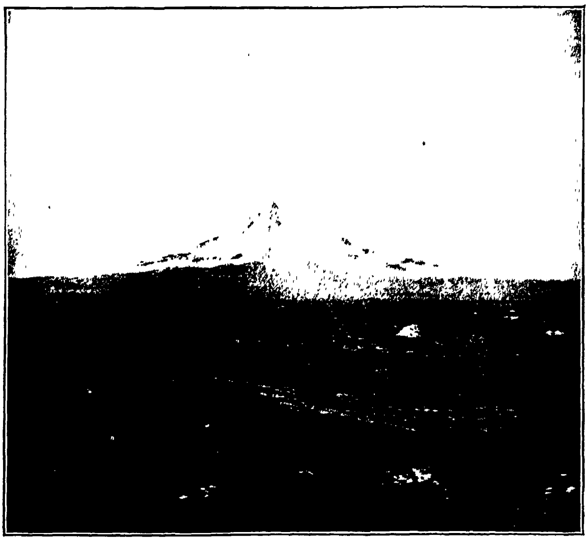


FIG. B. Shishaldin, Alaska, from Bering Sea. (Photograph by U. S. Fish Commission.)

abruptly from the sea and has two peaks of special prominence, known as Redoute and Iliamna, both of which are volcanic, and are reported to be about 11,000 and 12,000 feet high, respectively. Iliamna awakened from a period of repose in 1778, and has since kept in a state of mild activity with occasional explosive eruptions. In describing a visit to Cook's Inlet, Dall[1] remarks that it is only at a distance of thirty or forty miles that the majestic cone of Iliamna disengages itself from its associates and stands revealed in all its beauty. In the summer of 1895, when last seen by Dall, it was sending out five or six parallel columns of steam, and seemed peaceful enough. A few years ago, however, it was in violent eruption and discharged such a profusion of hot dust and lapilli that the timber over hundreds of square miles on the adjacent tableland was killed. As in the case of several of the recently active volcanoes of Alaska, the steam rising from Iliamna is usually so densely charged with volcanic sand and dust that it appears black. For this reason, the volcanoes are usually said to "smoke," although, in reality, little, if any, smoke is present, but only dust-charged steam. The accompanying illustration of St. Augustine, for which I am indebted to the United States Geological Survey, will serve to show the leading characteristics, not only of the volcanoes of Cook's Inlet, but of several others in Alaska. The timber line on the west side of Cook's Inlet has an elevation of about 1000 feet; above that limit is a belt of alpine flowers, which fade away into the desolate and frequently snow-covered regions about the mountain's summits.

[1] W. H. Dall, "Science," Vol. 3, 1894, p. 92.

Redoute volcano is similar to its companion just described, but, so far as I am aware, is unexplored.

St. Augustine. — In the southern portion of Cook's Inlet, near the west shore, rises the Island of St. Augustine, consisting principally of a single volcanic cone of striking grandeur. (Plate 3, Fig. B.) This volcano in 1880, as stated by Dall,[1] presented the appearance of a low dome, about 3800 feet high, without a peak. The island on which it stood was nearly circular in outline and about eight miles in diameter. To the northwest, it presented a bluff to the sea, but sloped more gently to the southeast. There are many rocks about it, which were formerly haunted by sea otter. Previous to the great eruption described below, this island was supposed to be of volcanic origin, but there is no authentic record of volcanic disturbances having occurred upon it. In August, 1883, what is described as "smoke" was seen to issue from its summit. On the morning of October 6, the inhabitants of Alexander village, sixty miles to the eastward, heard a heavy report, and saw clouds and flames issuing from the summit of the island. The sky became overcast, and a few hours later there was a shower of pumice dust. About half-past eight o'clock the same day, an earthquake wave, estimated at thirty feet in height, rolled in upon the shore, deluging the houses on the low land and washing the boats and canoes from the beach. Following the first great wave, came others of less height. The dust fell to the depth of several inches, and the darkness was so great that lamps were lighted. At night, flames were seen issuing from the summit of the island, and the snow, which

[1] "Science," Vol. 3, 1884, p. 92.

previously whitened it, disappeared. After the first disturbances were over, it was found that the northern slope of the summit had fallen to the level of the cliffs which form the shore, and the mountain appeared as if split in two in an east and west direction. Two previously quiet volcanoes on the Alaskan peninsula began simultaneously to emit smoke and dust; and in the ten-fathom passage between Augustine Island and the mainland a new island, approximately seventy-five feet high and a mile and a half in extent, made its appearance.

In August, 1895, Dall visited Cook's Inlet, and reports that an excellent harbor for small crafts, which existed on St. Augustine Island before the eruption of 1883, has been converted into a placid lagoon. A slender cloud of steam ascended from the summit of the volcano, which seems to have been built up by eruptions of lapilli and dust since the explosion that rent it asunder. The steam column serves as a barometer for the sea-otter hunters. When it ascends undisturbed by the upper-air currents and spreads out aloft like the well-known "pine tree" of Vesuvius, the natives put to sea in their frail skin boats, or kyaks, confident of two or three days of fine weather.[1]

Unimak Island. — This is the first or most easterly of the Aleutian islands and is separated from the Alaskan peninsula by a narrow strait, now nearly closed at its northern entrance by sand bars. The island is about sixty miles long in an easterly and westerly direction, and averages twenty miles in width. Its most prominent

[1] An account of the eruption of Mt. Augustine, accompanied by a sketch of the peak after being split in two, is given by Professor George Davidson, in "Science," Vol. 3, 1889, pp. 184–189.

topographic features are two volcanic mountains which are among the most interesting and instructive in Alaska. The highest of these, situated near the centre of the island and known as Shishaldin, has gracefully curving sides and rivals in beauty the far-famed sacred mountain of Japan. Its summit is bare of snow, although reported to be from 8000 to 9000 feet high. Since its first discovery by Russian navigators, it has been nearly always in a state of mild activity, as shown by the steam ascending from its summit, and occasionally has been the scene of violent explosions. To navigators it is one of the most familiar landmarks on the Alaskan coast.

The second volcano, Pogrumnoi, on the western portion of Unimak Island, is said to be between 5000 and 6000 feet high. Little else is known concerning it, however, except that it has frequently been in eruption.

As stated by Petroff,[1] Unimak Island has been and still is the theatre of the most constant volcanic activity in all Alaska. "Whole ridges of mountain peaks have been observed to split open and emit flames, torrents of lava, and clouds of ashes. These manifestations were always accompanied by the most violent earthquakes, tidal waves, and floods, the latter caused by the sudden melting of masses of ice and snow on the mountain tops. The greatest activity on record occurred in 1796, 1824, and 1825, and as late as 1827 burning lava was observed descending from the craters. Oonimak (Unimak) has also from time immemorial been the Aleutians' great storehouse, from which they obtained sulphur and obsidian, the latter being employed in the manufacture of knives, spears, and arrowheads. The Russian missionary, Veniaminof, who

[1] Report on Alaska in Tenth Census, 1884, p. 91.

witnessed one of these eruptions, describes the event as follows:

"On the 10th of March, 1825, after a prolonged subterranean noise, resembling a heavy cannonade, which was plainly heard on the islands of Unalaska, Akoon, and the southern end of the Aliaska peninsula, a low ridge on the northeast end of Unimak opened in five places with violent emissions of flames and great masses of black ashes, covering the country for miles around. The ice and snow on the mountain tops melted and descended in a terrific torrent five to ten miles in width on the east side of the island. Until late in the autumn the sea on that coast was turbid after this eruption. The Shishaldin crater, which up to that time had also emitted flames, continued to smoke only, while about midway between summit and base a new crater was formed, which was still smoking in the year 1831. On the 11th of October, 1826, a small peak in the interior of the island opened under violent explosion of fire and rain of ashes, which covered not only the southern end of Aliaska peninsula, but Sannakh and Ounga and other adjoining islands. Since that time smoke comes out of many places among the loose masses of rocks on the mountain side, and all the streams and ponds in the vicinity are hot enough to emit steam in midsummer."

From the graceful outlines of Mt. Shishaldin, shown in the illustration forming Plate 15, Fig. B, reproduced from a photograph taken about ten miles at sea to the north, it appears that the mountain is a lapilli cone built principally of material extruded during mild explosions. Steam was seen at the summit of the mountain in the summer of 1895. So far as known, no one has ever

ascended Shishaldin. A study of this splendid volcano would certainly be productive of much valuable information.

Bogosloff Island.—In Bering Sea, about forty miles west of the northern extremity of Unalaska Island, and in latitude 53° 58′, longitude 168° W., there is an island composed entirely of volcanic rock which has been formed by eruptions within historic times. The island is known to the Russians as Ioanna Bogoslova (St. John, the theologian) and to the natives of the Aleutian islands as Agáshagok; it is now commonly called "Bogosloff."

Near the locality where Bogosloff now rises, an isolated rock was long ago known to the natives of the Aleutian islands, and represented on certain Russian charts bearing the date of 1768–69. This rock is mentioned by Captain Cook, who saw it in 1778, and named it Ship Rock.

It is stated by Dall[1] that in 1795 the natives on Unalaska noticed what appeared to be a fog in the neighborhood of the rock, which did not disappear when the rest of the atmosphere was clear. In the spring of 1796, one of the natives more courageous than his companions visited the locality and returned in terror, saying that the sea all about the rock was boiling, and that the supposed fog was the steam rising from it. The disturbance was accompanied by activity in the craters on Unimak and Unalaska islands. In May, 1796, a considerable mass of material was upheaved and the major part of the present island was formed.

Accounts of the appearance of Bogosloff by natives and Russian observers, cited by Dall, Petroff, and others, do not furnish answers to many of the questions that a student of volcanic phenomena would like to ask.

[1] "Science," Vol. 3, 1884, pp. 89–93.

Unsuccessful attempts to land on Bogosloff were made by Dall in 1872, and again in 1873. The island then had a sharp, narrow summit ridge about 850 feet high, covered with inaccessible pinnacles, but there was no appearance of a crater. The shores were mostly precipitous, except at the southern end, where the waves and currents had formed a small spit of talus, on which a landing could be made in favorable weather, but the short swell produced a heavy surf. When seen through a glass, from a distance of four miles, the island appeared of a light purplish-gray color, devoid of vegetation or water, and covered with myriads of birds.

In October, 1883, a violent eruption occurred at Bogosloff, at the same time that Mt. St. Augustine, in Cook's Inlet, was active. The island was enveloped in steam and a new crater is reported to have been formed, which has since been more or less active. Great changes in the form of the island also occurred, and near at hand, where a great depth of water was formerly reported, land was elevated to a height of nearly 300 feet. At the time of the eruption just referred to, a dark cloud of dust covered the sky northward of Unalaska Island and hung near the surface of the sea for about half an hour. It excluded the light of the sun and was accompanied by a rise of temperature. The cloud then drifted over Unalaska, and dull gray volcanic dust of extreme lightness fell in considerable abundance. During the eruption, Makushin, one of the most recently active volcanoes on Unalaska Island, was quiet, although earthquake shocks were felt. After the eruption a new island was discovered near the former one, at a locality where ships had previously sailed in safety; and in September, 1883, was reported to be "a mass of

fire," probably red-hot rocks, and steam. This new island, situated half a mile northwest from "Old Bogosloff," when first seen was conical in shape, with an irregular outline, 500 to 800 feet high, and about three-quarters of a mile in diameter.

Bogosloff Island was visited by Lieutenant J. C. Cartwell and Surgeon H. W. Yemans of the U. S. Revenue Marine steamer *Corwin*, in 1884, and many instructive observations made.[1]

Approaching the island from the northeast, Cartwell found it to have the appearance of being divided into two parts (Plate 16, Fig. A), the northern portion (New Bogosloff) being in a state of eruption, and the southern portion (Old Bogosloff) a much more serrate rock rising almost perpendicularly from the sea, without signs of activity. Between the two and nearer the northern part of the New Bogosloff, a tower-like rock rises with a slight inclination toward the north to a height of eighty-six feet. At a distance, the central rock might easily be mistaken for a sail upon the horizon, and for this reason is called Ship Rock or Sail Rock. A nearer approach discloses the fact that the two elevations are connected by a low, flat beach, free from rocks, which affords an excellent landing-place for small boats.

The narrow isthmus connecting the two prominent portions of the island is composed of a mixture of fine black sand and small oölitic stones. This isthmus is evidently of the nature of a sand bar formed by the waves, of material washed from the higher portion of the island; pos-

[1] Report of the Cruise of the Revenue Marine Steamer *Corwin* in the Arctic Ocean in the Year 1884, by Captain M. A. Healy, U.S.R.M., Commander, Washington, 1889, pp. 39–44.

sibly a slight elevation is here recorded; the newer portion of the island being at first disconnected, as was reported by some observers.

As related by Cartwell: "The sides of New Bogosloff rise with a gentle slope to the crater. The ascent at first appears easy, but a thin layer of ashes, formed into a crust by the action of rain and moisture, is not strong enough to sustain a man's weight. At every step my feet crushed through the outer covering and I sank at first ankle-deep and later on knee-deep into a soft, almost impalpable dust which arose in clouds and nearly suffocated me. As the summit was reached, the heat of the ashes became almost unbearable, and I was forced to continue the ascent by picking my way over rocks whose surfaces, being exposed to the air, were somewhat cooled and afforded a more secure foothold.

"On all sides of the cone there are openings through which steam escaped with more or less energy. I observed from some vents the steam was emitted at regular intervals, while from others it issued with no perceptible intermission. Around each vent there was a thick deposit of sulphur, which gave off suffocating vapors." No appearance of lava streams or of cinders was noted. Small quantities of rock froth, consisting of unfused particles in a semi-fused mass, were seen, but during its extrusion the rocks do not appear to have been sufficiently heated to cause true fusion.

A walk of a third of a mile along the beach mentioned above brings one to Old Bogosloff, where the beach abruptly terminates against rugged rocks, which rise almost perpendicularly to a height of 325 feet. Surgeon Yemans states that the origin of New Bogosloff was first

made known by Captain Anderson of the schooner *Matthew Turner*, who saw it on September 27, 1883, and reported that great volumes of steam and ashes were erupted from the summit and also from numerous fissures on the sides and base. At night bright reflections from the highly heated interior were distinctly visible.

Samples of rock and dust collected by the gentlemen whose reports have just been cited were examined by G. P. Merrill of the United States National Museum, and ascertained to be hornblende andesite. The dust was found to be identical with dust that fell at Unalaska, sixty miles distant, at the time of the eruption. The rocks are considered as ejected fragments of some underlying strata and not recent lava flows, thus confirming Cartwell's observation in reference to the absence of molten lava. An account of the mineralogical and chemical composition of the material forming Bogosloff may be found in "Science," Vol. 4, 1884, p. 524.

Although not personally familiar with Bogosloff, I venture to suggest from what I have seen in connection with other volcanoes, that the formation of the island was due to the outwelling of viscous lava, which hardened at the surface so as to resemble the rough, scoriaceous surface so common on lava flows. The lava, being quickly cooled, did not flow as a stream, but as in the case of some of the Mono craters previously described, rose in rugged, scoriaceous masses, without much explosive violence. Nothing resembling a crater ring of lapilli and dust is reported as surrounding the elevated crags of lava.

Dall remarks that other islands similar to Bogosloff in origin are known in the same general region.[1] Mention

[1] "Science," Vol. 3, 1884, p. 92.

FIG. A. Bogosloff, Bering Sea, 1884. (Photograph by U. S. Fish Commission.)

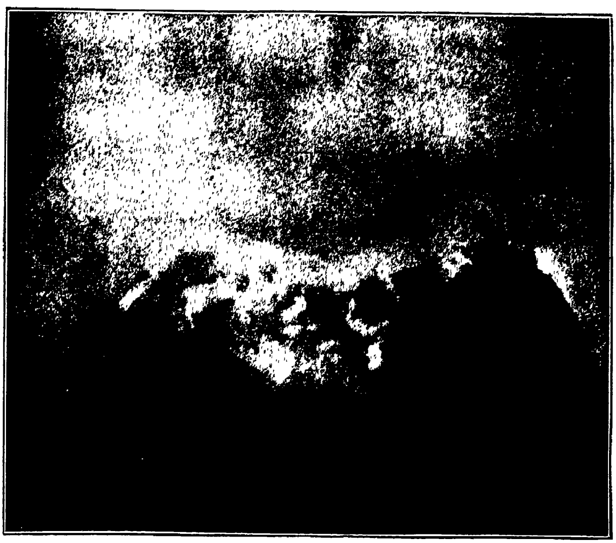


FIG. B. New Bogosloff, Bering Sea, 1884. (Photograph by U. S. Fish Commission.)

is made of Koniúgi and Kasátochi in the western Aleutian chain, and of Pinnacle Island near St. Matthew's Island, Bering Sea. The last differs from Bogosloff in having the crest deeply channelled. It is reported that light has been seen in the fissures of Pinnacle Island "within the last few years by navigators passing in the night," though there is no record of steam having been noted.

Unalaska Island. — The Island of Unalaska is next to the largest and in the development of Alaska the most important of the Aleutian chain. It is about 120 miles long by 40 miles wide, and has a deeply indented shore line. Its borders are bold and its surface exceedingly rugged. Dominating the wild, treeless landscape to be seen while sailing along its shores, and as observed by the writer from a steep-pointed summit left by erosion, near its northeast extremity, stands Mt. Makushin, with an elevation of 4000 or 5000 feet. This mountain is of volcanic origin, although it has not been in active eruption, so far as can be learned from Russian records or from the traditions of the natives, within several generations. Steam still issues at intervals from its summit, and earthquakes and subterranean noises which seem to proceed from the mountain indicate that it should be considered a dormant rather than extinct volcano.

Petroff states in his report in the Tenth Census, page 92, that Russian naval officers who visited Unalaska at long intervals in the early part of this century, assert that many of the points and ridges on Makushin were observed to have changed in outline owing to volcanic action between their several visits.

North of Makushin and in plain view from the hills about Iliuliuk, the village usually visited by vessels bound

for Bering Sea and the Arctic, rises another conical volcanic mountain about 3000 feet high. This volcano has long been extinct and its sides are scored with erosion channels.

Central and Western Aleutian Islands.—Information concerning the volcanoes of the Aleutian islands is for the most part so meagre and of such a general nature that to attempt to compile all of it would result in little more than a catalogue of names, with a few dates at which eruptions have been seen. Such compilations have already been made by Grewingk, Dall, and Petroff, as previously stated. As the reports of these explorers are in many libraries, it is unnecessary to republish the catalogue of volcanoes they contain.

On many of the islands there are volcanic mountains with craters, and deposits of lava, lapilli, dust, obsidian, etc., are abundant. Hot springs occur at many localities. The general appearance of these volcanoes as seen from the sea is illustrated by the accompanying photograph of Mt. Cleveland on the Islands of the Four Mountains and of a similar cone known as Pavaloff volcano on the Alaskan peninsula. These pictures, together with the illustration of Shishaldin, will serve to give some idea of the topography of the volcanic belt of southwestern Alaska.

Summary.—Meagre as is the accurate information concerning the large number of volcanoes in southern Alaska and on the Aleutian islands, it is sufficient to show that a wonderfully interesting region there awaits careful study. The most instructive facts now in hand relate to the distribution of the volcanic vents in a well-defined belt. This, taken in connection with the topography of the

region, and the records of recent upheavals as shown by elevated beach lines, indicates that profound fractures have there occurred, accompanied by faulting and the elevation of plateaus, like that bordering Cook's Inlet on the west. The geological structure in much of southwestern Alaska, so far as can be judged, resembles that of the Great Basin; the main geographic features being due to the upheaval and tilting of great blocks of the earth's crust. The association of numerous active volcanoes with a narrow belt of fractures is significant, and, as in Central America, suggests that forces tending to break the earth's crust when concentrated along narrow belts are able to keep open communications with the earth's highly heated interior, much more effectually than when the disturbances affect a broader region, as in that portion of the Cordilleras which crosses the United States.

In closing this sketch of the volcanoes of North America, I feel that the impression obtained by the reader will be that a vast field of great interest to the student of volcanic phenomena has been pointed out, but that our information concerning it is meagre and unsatisfactory. If, however, what I have written serves to stimulate inquiry and encourage fresh exploration and study, I shall feel more than repaid for the labor expended in compiling this book.

CHAPTER VI

DEPOSITS OF VOLCANO DUST

Among the important contributions of volcanic origin, made to the surface of the land over large proportions of North America, are certain deposits of fine, dust-like material, which was blown out of volcanoes in widely separated regions and distributed over great areas by the wind. Several references to these highly interesting accumulations have been made in preceding chapters, but at the risk of some repetition, a brief summary of what is known concerning them it is believed will be instructive.

Distribution.—Travellers in Central America and Mexico frequently refer to the deep, rich soils of that region, which consist largely of what are usually termed volcanic ashes. Over extensive areas the soil is composed of disintegrated volcanic rock, which grades on one hand into fragments of pumice and lapilli, and on the other hand passes into fine volcanic dust. Much of this material is known to have resulted from the explosive eruptions of Conseguina, Izalco, Jorullo, and other volcanoes that have been in eruption since the Spanish conquest; but the greater part of the soil-making volcanic débris came from prehistoric eruptions.

Under the influence of the moist, warm climate, prevalent in the greater part of Central America and Mexico,

the fine volcanic material strewn over the surface rapidly decomposes, and becomes available as plant food. An efficient method of natural fertilization and soil-renewal is thus illustrated.

In the Sierra Nevada, and over large portions of the Great Basin, deposits of volcanic dust many feet in thickness are frequently met with.[1] These occur both on the surface and especially at the mouths of gorges in the uplands, where the dust has been washed down and accumulated in alluvial cones, and interbedded with the sediments of Pleistocene lakes. Evidently the volcanic eruptions which furnished the dust occurred both in Pleistocene and Recent times. As explained in a previous chapter, these deposits occur in great abundance about the Mono craters, and have been traced with considerable certainty to a distance of fully 200 miles northward from them. Near the Mono craters, these deposits are coarse and are mingled with gravel-like lapilli, but become finer and finer, and less and less abundant, with increasing distance from their source. The similarity of the volcano dust occurring at a distance—as in northern Nevada—to that found abundantly in Mono valley, is not confined to physical properties, but embraces chemical composition as well. Analysis of volcanic dust collected in Truckee canyon, near Pyramid Lake, Nevada, and of the pumiceous rhyolite forming a large part of the Mono craters, shows an almost identical composition. The proof is then almost conclusive that the widely distributed dust

[1] I. C. Russell, "Quaternary History of Mono Valley, California," United States Geological Survey, 8th Annual Report, 1886–87, pp. 386, 387. "Lake Lahontan," United States Geological Survey, Monograph, Vol. XI, 1885, pp. 146–149.

came from the same source as the lava forming the volcanic mountains in Mono valley.

Dust-like deposits of volcanic origin are of common occurrence in Utah, especially in the vicinity of Salt Lake City, and attain a thickness in several instances of from thirty to fifty feet or more. Some of these deposits are interbedded with lacustral sediments of Tertiary age; but others are probably much more recent, although but little definite information concerning them is available.

Widely spread deposits of volcanic dust occur over great areas in Montana, South Dakota, Nebraska, and Kansas. Some of these beds are of Tertiary age, others occur beneath fine, clay-like material termed *loess*, of Pleistocene age, while still others occupy depressions in the present surface, or fill hollows formerly occupied by lakes, and are clearly post-glacial.

The deposits of volcanic dust in Nebraska, as stated by Professor E. H. Barbour,[1] have been discovered in twenty counties which are so situated as to show that the entire strata were covered by the dust showers. These deposits were formed after the land had its present topography, and are coarsest and in greatest abundance, being sometimes fifty feet thick, in the southwestern portion of the state, and become gradually thinner and finer when traced eastward. This arrangement indicates that the volcano from which the material was derived is situated to the southwestward of the western part of the state.

[1] Nebraska Academy of Science, Vol. 5, 1894–95, pp. 12–17. In this essay, illustrations showing the appearance of the dust when examined with the aid of the microscope are given, together with drawings of the flakes composing ground pumice, for comparison.

As to color and texture, some of the Nebraska deposits are as pure and fine as the best ground pumice of commerce. From this nearly pure-white material there are all gradations to that which is discolored with iron and organic matter, and so coarse and mingled with so much silt that one cannot decide whether the dust or the matter mingled with it predominates.

Thick deposits of volcanic dust similar in nearly every particular to that of California and Nevada, and in the region referred to east of the Rocky Mountains, occur at numerous localities in Oregon and Washington. Many of these deposits contain the leaves of Tertiary plants, or are associated with lacustral sediments and lava flows in such a manner as to show that they are of Tertiary age. In some instances, however, accumulations of the same kind of material are found on the surface, and in such relation to the present topography as to demonstrate their recent origin. At a late date, but not determinable in years, a light shower of fine, pure-white volcanic dust fell on an area of fully 10,000 square miles in southeastern Washington and adjacent states. This deposit has been so commingled with the soil that its presence is seldom recognizable, except at the mouths of ravines and gulches in the sides of the valleys, where it has been concentrated by small streams so as to form alluvial cones. In many such localities a depth of from ten to twenty feet or more of fine, white, highly siliceous dust may be seen. This last light shower of dust, although of slight importance in comparison with the deposits many feet in thickness of older date, in the same region, yet in the aggregate added many thousands of tons of fertilizing material to the region over which it

was spread. The volcanoes from which the abundant volcanic dust deposits of the Pacific Northwest were derived are unknown, but were probably in the Cascade region. The more recent dust showers may reasonably be ascribed to the volcanoes of which Baker, Rainier, and Shasta are representatives.

In Alaska and adjacent portions of Canada, still other extensive deposits of volcanic dust of recent date are known. The writer, while journeying up the Yukon River in 1889,[1] observed above the mouth of Pelly River, a conspicuous white band from eight to twelve inches thick, in the upper portions of the river terraces, which was traced for fully 200 miles. This deposit of remarkably pure volcanic dust had previously been noted in adjacent regions and was more fully examined by Hayes in 1881.[2] These various observations show that it occupies an area of fully 52,280 square miles, and varies in thickness from a few inches on its northeast border, to between 75 and 100 feet near its southwest margin. Its volume has been computed by Hayes to be in the neighborhood of 165 cubic miles. The volcano from which this vast eruption of fine dust was derived is as yet unknown, but from its distribution, and its increase both in thickness and in coarseness toward the southwest, the point of eruption is judged to be some seventy-five miles northwest of Mt. St. Elias.

This Alaskan deposit is pure white, except when impurities are present, and indistinguishable, at least in its

[1] I. C. Russell, "Notes on the Surface Geology of Alaska," in Geological Society of America, Bulletin, Vol. I, 1890, pp. 145, 146.

[2] C. W. Hayes, "An Expedition through the Yukon District," in "National Geographic Magazine" (Washington, D.C.), Vol. 4, 1892, pp. 146–150.

physical properties, from the similar material found so abundantly in California, Oregon, and Washington. In Alaska, the dust rests in part on moraines which have been abandoned in recent times by the still retreating glaciers, and occurs in post-glacial terraces along the Yukon, and is therefore of recent origin.

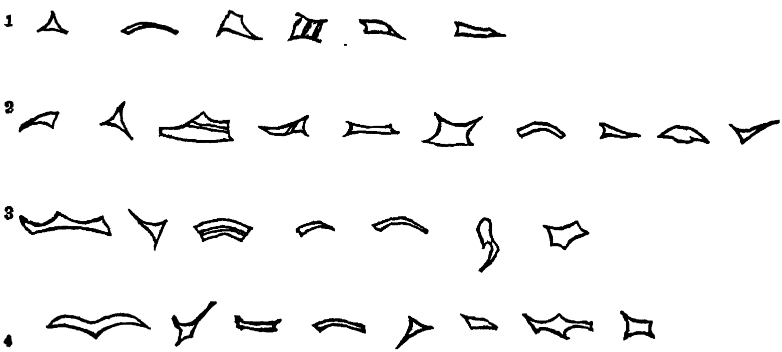
The great abundance of volcanic dust in the Cordilleran region, its wide distribution, and its occurrence in numerous instances at many horizons in the same vertical section, is evidence that vast areas in western North America have been shrouded in darkness at many separate periods, and have time and again witnessed horrors like those which overwhelmed Pompeii and Herculaneum. Disasters similar to those accompanying the eruptions of Conseguina and Krakatoa occurred at intervals throughout the Tertiary and Recent history of fully one-half of North America. Events of a like tragic character are also recorded by pre-Carboniferous deposits of volcanic dust, now consolidated into hard rock, in the Appalachian Mountains, near Boston, and on the shores of Lake Superior.[1]

The volcanic dust of the Pacific states sometimes contains the bones of mammals and is frequently charged with quantities of leaves, showing that some of the tempests generated by volcanic agencies were disastrous to animal and plant life. These and related disturbances in environment probably had much to do with the modification and extinction especially of the higher mammalian species.

Physical and Chemical Properties. — The leading physi-

[1] N. H. Winchell and U. S. Grant, "Volcanic Ash from the North Shore of Lake Superior," in "The American Geologist," Vol. 17, 1896, pp. 211–213.

cal characteristics of the volcanic dust, referred to above, are its whiteness, unless adulterated with other substances, and the angular character of the flakes of glass of which it is composed. The individual flakes are usually too small to be seen by the unaided eye, and in nearly all respects closely resemble powdered pumice. They may be almost precisely duplicated by grinding ordinary glass, or common obsidian, or pumice, in a mortar. When examined under a microscope, the dust



1. Volcanic dust which fell in Norway, March 29 and 30, 1875.
2. Volcanic dust emptied from Krakatoa, August 27, 1883.
3. Volcanic dust from the Truckee River, Nevada. Quaternary.
4. Volcanic dust from Brakleast Hill in Saugus, Massachusetts. Pre-Carboniferous.

FIG. 11. Volcanic dust. (J. S. Diller.)

is found to consist of angular flakes and shreds of glass, in which irregular cavities are frequently detectable. There is usually an absence of crystalline fragments, but this is not always the case.

The appearance of a sample of volcanic dust from Truckee canyon near Pyramid Lake, Nevada, which is representative of a large number of similar deposits between southern California and Alaska, when examined under a microscope, is shown in the above figure,

together with drawings of similar material erupted by existing volcanoes, and also an ancient example of like origin but now consolidated into a hard rock, from near Boston. This figure is borrowed from an article by J. S. Diller, on volcanic sand which fell at Unalaska, on October 20, 1883.[1] In this instructive essay, much additional information concerning the nature and origin of the deposits under discussion may be found.

One of the most striking facts in connection with the widely distributed deposits of volcanic dust enumerated above, is their marked similarity in both physical and chemical characteristics. At almost all of the hundreds of localities examined by the writer between Mono valley and the Yukon, the material is a fine, white, highly siliceous powder, which closely resembles pure infusorial earth. The only exceptions to be noted are where the deposits are impure on account usually of the presence of silt and sand; this occurs especially when the deposits are stratified, showing that in part the material composing them was washed into lakes or other water bodies, and when the dust is mingled with larger fragments of a similar origin, and grades into volcanic sand and lapilli. Additional facts concerning what geologists term *pyroclastics,* that is rock material reduced to fragments through the agency of heat, may be found in many text-books of lithology.

Although but few quantitative chemical analyses of volcanic dust deposits here considered are available, yet it is believed, from many qualitative examinations, that the two complete analyses given below represent very nearly their average composition.

[1] "Science," Vol. 3, 1884, pp. 651–654.

ANALYSES OF VOLCANIC DUST

Constituents.	No. 1.	No. 2.
Silica (SiO_2)	71.15	68.91
Alumina (Al_2O_3) and iron (Fe_2O_3)	15.95	6.12
Lime (CaO)	0.85	3.44
Magnesia (MgO)	0.41	—
Manganese (MnO)	trace	—
Potash (K_2O)	3.36	0.36
Soda (Na_2O)	4.94	3.09
Organic matter	—	8.75
Sulphuric acid (SO_3)	—	8.88
	100.57	99.55

No. 1. From Truckee canyon, Nevada; analysis by T. M. Chatard; in U. S. Geological Survey, Monograph, Vol. 11, p. 147.

No. 2. From Nebraska; analysis by H. H. Nicholson; in Nebraska Academy of Science, Vol. 5, 1894–95, p. 13.

The sample from Nebraska is evidently less pure than that from Nevada, as it contains organic matter and probably also sulphate of lime, which have been added to the material that fell as dust. Three analyses of volcanic dust probably of Tertiary age, from Montana and Idaho, published by G. P. Merrill,[1] show from 65.56 to 68.12 per cent of silica. The marked feature in the composition of the dust is the high percentage of silica. Evidently the dust owes its origin to the disintegration of acid lava. So far as my own observations extend and so far, I believe, as has been reported by others, no deposits of volcanic dust of a basic character have been discovered in North America.

[1] "Note on the Composition of Certain 'Pliocene Sandstones' from Montana and Idaho," in "American Journal of Science," Vol. 32, 1886, pp. 199–204.

The richness of volcanic dust in silica has been noted especially by Diller,[1] who states that in general volcanic *sand* (fine lapilli) is composed chiefly of crystalline fragments, and contains a lower percentage of silica than the lava to which it belongs; while volcanic *dust* contains more silica than the lava effused from the volcano from which it was derived. In explanation of these interesting facts, the author just cited states that "The difference in chemical composition between volcanic sand or dust, and the lava to which it belongs, appears to be directly proportionate to the amount of crystallization which had taken place in the magma before its effusion. It is well known that crystals are frequently, and sometimes abundantly, developed in a magma; so that, before its extrusion, the magma may be regarded as made up of a crystalline, solid portion, and an amorphous, more or less fluid portion. These are generally thoroughly intermingled, but occasionally they are arranged, as in obsidian, in alternating bands; and they differ from each other in several important particulars, besides those already mentioned. The earliest products of crystallization are basic minerals, such as the ores of iron, hornblende, and mica; and as the process continues, the amorphous portion of the magma becomes more and more siliceous. On this account, the crystalline portion of the magma does not contain as high a percentage of silica as that which is amorphous. In the process of crystallization the gases absorbed in the magma are rejected from the crystallizing substances, and accumulate, under enormous tension, in the portion which is amorphous. In this manner the non-crystalline portion of the magma becomes stored with explosive compounds,

[1] J. S. Diller, "Science," Vol. 3, 1884, pp. 653, 654.

under such stress, that when the pressure is relieved, they may blow it to fine, siliceous glass-dust; while the crystalline, solid, basic portion of the magma, pulverized rather by external than internal forces, is reduced to sand."

Among the illustrations of the fact that volcanic dust is frequently richer in silica than the parent lava, the composition of the material discharged by Krakatoa, in 1883, is cited. The dust resulting from that eruption, and widely distributed over the earth, has been found to contain 65.04 per cent of silica; while the lava effused at the same time contains but 62 per cent of silica.

The abundant occurrence of acid volcanic dust, and the fact that basic material of a similar physical character has not been found in the deposits under consideration, is apparently not fully explained, however, by the hypothesis just quoted. In addition to the changes produced in a magma by fractional crystallization, it may be suggested that the chemical composition of the magmas as a whole, from which the dust was derived, plays an important part. Acid magmas, as stated in a previous chapter, are of different fusibility, and generally form viscous fluids; while basic magmas are more easily fused and form more perfect fluids. The viscous magmas, when expanded by occluded steam and gases, become brittle on the loss of a small amount of heat, and are in a condition to be shattered; while the more fluid magmas allow the occluded steam and gases to escape without violent explosions. This suggestion is in harmony with the well-known fact that most pumice is rich in silica.

While eruptions of basic magmas may form large quantities of lapilli, and yield dust particles by the attrition

of projected fragments, the proportion of dust due to the explosion of occluded steam would be comparatively small; on the other hand, siliceous and usually viscous magmas would be shattered by the explosion of the steam contained in them, and give origin to an abundance of dust-like particles. The presence, therefore, of vast accumulations of siliceous volcanic dust, and the absence of basic material of similar nature in the Cordilleran region, is rather to be accounted for by the fact that volcanoes effusing acid lava manufacture vastly more dust particles than those from which only basic lavas are extruded. The fractional crystallization that takes place in cooling magmas cited by Diller, while no doubt an important factor favoring the production of acid volcanic dust, seems too delicate an adjustment to alone account for the vast abundance of acid volcanic dust and the absence of basic material of like character over a large portion of North America. In Oregon and Washington, for example, the igneous rocks that occur in greatest abundance are of the basic type, while all of the dust deposits known are rich in silica. Rather than expect that a basic magma like that producing basalt could, by fractional crystallization, give origin to highly acid dust, it seems more rational to assume that the basic lavas came from different eruptions than the volcanic dusts so abundantly associated with them.

Economic Importance. — Volcanic dust is used as an abrasive principally in the form of polishing powder and as an ingredient in friction soap. It is serviceable for most if not all of the uses for which ground pumice and diatomaceous earth are employed. Experiments have shown that it may be used with satisfactory results in

connection with paint as a substitute for sand in certain processes of painting, particularly when the surface coated is exposed to the weather. Other uses for this abundant and remarkably clear, white, siliceous powder will no doubt be found.

CHAPTER VII

THEORETICAL CONSIDERATIONS

ALL modern theories that have been advanced to account for volcanic phenomena rest on still other and more general theories in reference not only to the condition of the interior of the earth, but to the origin of the earth itself.

The meteoric hypothesis of Lockyer, which may be considered as a modification of the earlier nebular hypothesis of Laplace, more nearly satisfies the facts observed in reference to the present condition and to the origin of the earth, than any other explanation that has been advanced, but cannot be considered as entirely satisfactory. Without attempting to discuss the profound problems referred to, we will assume, for the present, that the earth reached its present condition after a long period of cooling from a molten condition, during which a cool and solid crust was formed about a still highly heated interior.

Internal Heat of the Earth. — As is well known, there are abundant observations to show that diurnal changes of temperature do not affect the earth below a depth of about three feet; while seasonal changes of temperature do not occur below an average depth of about forty feet. Any temperatures that the earth may have below this depth, therefore, cannot be due to the radiant energy of the sun. Below the depth in the earth to which the influences of seasonal changes are felt, there is, as shown by

observation, a zone of invariable temperature, below which the temperature increases in general at the rate of one degree Fahrenheit, for each fifty or sixty feet of descent. At this rate of increase, a temperature of 212° would be reached at a depth of about 8000 feet. At a depth of thirty miles the temperature would be such that all known substances would melt under ordinary atmospheric pressure. The measurements on which these well-known conclusions are based do not extend below a depth of approximately one mile, but are sustained, at least in a qualitative way, by the phenomena observed in volcanoes and hot springs. The accepted conclusion is that the interior of the earth below a depth of a very few thousand feet is intensely hot.

Computations made by Tate, based on the observed rate of increase of temperature towards the centre of the earth, and the rate at which rocks conduct heat, have shown that the internal heat of the earth is being carried away and dissipated in space at the rate of 250 units of heat per annum per square foot of the earth's surface; the unit of heat used being the amount of heat necessary to raise the temperature of one pound of water one degree Fahrenheit. The computed annual loss of heat from each square foot of the earth's surface is sufficient to warm one and one-fourth pounds of water from the freezing to the boiling point. If we accept the conclusion of Laplace, Lockyer, and others, — that the earth was formerly in a molten condition, — it follows that the rate at which the earth has been losing heat was formerly greater than now, and that it will continue to decrease in the future. Another inevitable conclusion is that this loss of heat has been accompanied

by contraction. The earth is smaller than formerly and will continue to decrease in size.

Condition of the Earth's Interior. — The observed increase in temperature with depth in the earth naturally lead to the supposition that the interior is in a molten condition; but when the influence of pressure on the fusing point of rocks was considered, it became questionable whether any portion of the interior could exist in a liquid condition.

Astronomers have shown conclusively, as it appears, that the earth behaves, in reference to the attraction of the sun and moon, like a rigid sphere; the conclusion being that the earth is as rigid as a sphere of steel of the same dimensions.

Geological observations have proven conclusively that the earth's surface is continually in motion. Portions of the surface are undergoing elevation, while other portions are being depressed. The proof is abundant, also, that similar movements have been in progress since the dawn of geological history. The differential movements of adjacent areas in numerous instances are measured by tens of thousands of feet.

These apparently opposite conclusions reached by astronomers and geologists may be harmonized on the hypothesis that the interior of the earth, although highly heated, is solid by reason of the pressure to which the rocks composing it are subjected, but that they would become plastic or even highly fluid if the pressure was sufficiently relieved. This condition of the earth's interior is expressed by the term *potentially plastic;* that is, the material of which it is composed is solid by reason of the pressure under which it exists, but would

become plastic, by reason of its heated condition, if the pressure were relieved. In brief, the conception of the condition of the earth that is in harmony with the conclusions reached by both astronomers and geologists is, that it consists of a comparatively thin, rigid shell, termed the earth's crust, enclosing a highly heated and solid, but potentially plastic, sphere, — the passage from one to the other being gradual. The inner sphere sustains the pressure of the outer shell, or, more accurately, pressure increases with depth; but if pressure is sufficiently relieved on a portion of the heated interior, it will at once become plastic or liquid, and in a condition to flow under moderate pressure.

Changes on the earth's surface — such as the removal of material from one locality to another, through the action of rivers, etc. — lead to changes in the pressure of the crust on the potentially plastic interior, and tend to change its shape. Contraction, accompanying loss of heat, decreases the size of the inner sphere, and the rigid crust has to adjust itself to the shrinking mass within; this it does by folding or bending, and by fractures and the overthrusting or underthrusting of the rocks on the sides of the break. Accompanying these changes are both regional and local elevations and depressions of the earth's surface.

A fracture in the earth's crust, if it reached from the surface to the highly heated interior, would be equivalent to a relief of pressure. The highly heated and potentially plastic rocks in the vicinity of such a fracture would at once become plastic or even highly fluid, and be forced into the break by the pressure of adjacent rocks. When the pressure was sufficient to force the

molten material to the surface, volcanic phenomena would ensue. Before testing this hypothesis, other facts concerning the earth's crust should be considered.

Intrusive Rocks. — Observations in many regions have shown, as stated in the first chapter of this book, that fractures have occurred in the earth's crust at many different geological periods, and been injected with molten rock which has been forced into the fissures from below. Fissures filled in this way are known as *dikes*. They vary in width from a few inches or even a fraction of an inch to hundreds of feet, and are frequently scores of miles in length. They may appear as vertical or variously inclined sheets cutting across the bedding of stratified or other rocks. In many instances, molten rock has been forced between stratified rocks, and, on cooling, formed sheets having the same bedded arrangement as the enclosing layer. Layers of crystalline rock originating in this manner are termed *intruded sheets,* in distinction from surface overflows, or *extruded sheets*. Under certain conditions not well understood, molten rock forced into the earth's crust from below, instead of breaking through the strata or spreading out between them, causes them to rise, and cisterns of molten material are formed beneath them; a series of uplifts are thus formed, which are known as plutonic plugs, laccolites, and subtuberant mountains.[1] These various classes of igneous intrusions occur in the earth's crust, sometimes at great depths, as is shown by the amount

[1] I. C. Russell, "Igneous Intrusions in the Neighborhood of the Black Hills, Dakota," "Journal of Geology," Vol. 4, pp. 177–194. "On the Nature of Igneous Intrusions," "Journal of Geology," Vol. 4, 1896, pp. 23–43. "Igneous Intrusions and Volcanoes," "Popular Science Monthly," December, 1896.

of rock eroded away so as to expose them at the surface, and must have been forced in against an enormous pressure. The force or pressure which caused these intrusions is so vast in many instances that one fails to comprehend its magnitude. As described in the papers just referred to, great mountain ranges in the central part of North America — like the Black Hills of Dakota, Big Horn Mountain, Wyoming, and the eastern range of the Rockies in Colorado — belong to a class of uplifts designated as subtuberant mountains, and are believed to owe their origin to great reservoirs of molten rock forced into the earth's crust.

Relation between Igneous Intrusions and Volcanoes. — As we have just seen, dikes result from the filling of fissures with molten rock, which in most instances is forced in from below; the best explanation that has been given of the origin of intruded sheets, plutonic plugs, laccolite, and subtuberant mountains, is that intruded rock was forced upward through fissures in the deeper part of the earth's crust and expanded in various ways in its more superficial portions, and especially in regions of horizontally stratified beds. The primary conditions leading to the origin of these various forms of intrusions, are: (1) deeply seated reservoirs of plastic or potentially plastic rock in the earth's crust or below it, and under great pressure; (2) fissures formed in the crust and opening into the deeply seated reservoirs.

Under these conditions the highly heated material below the surface, when fissures were formed in the crust, would become plastic, or perhaps highly fluid, and being under great lateral pressure, would be forced upward into the fissures. The behavior of the material injected into

the earth's crust in this manner would vary according to the character of the fissures, the depth to which they reached; the structure of the rocks through which the magmas rose, whether stratified or massive, and if stratified, whether horizontal or inclined, and if water-charged or not; the nature of the magmas themselves, whether easily fusible or refractory, etc. The influence of these various conditions has been considered in the essays just referred to.

Volcanoes in many instances are known to be located on fissures in the earth's crust. The dissection of volcanic mountains by erosion has shown, in many instances, that the conduits through which the lava rose were fractures, which, being filled with molten rock, formed dikes as the magma cooled.

It is evident, then, that igneous intrusions and volcanoes are phases of the same process. Fissures originating in the lower portions of the earth's crust, but failing to reach the surface, would, on being filled with molten rock, be transformed into dikes, and in regions where great thicknesses of horizontally stratified beds occur, might lead to intruded sheets, laccolites, etc. If the fissures extended from the highly heated interior to the surface, — or if less extensive fissures are formed in the lower portion of the crust, and the force of the injected magma, acting like a wedge, prolong them to the surface, — molten rock would be poured out and a surface overflow occur, that is, a volcano would be formed. A single fissure might thus lead to the origin of intrusions of various forms, and also to volcanic eruptions of various kinds, according to the modifying conditions. The primary conditions leading to surface discharges of molten rock

or extrusions, are the same as those which give origin to subterranean injections or intrusions.

Source of the Steam of Volcanoes. — The most striking feature of volcanic eruptions and one, so far as now known, always present, is the abundant escape of steam. Steam frequently escapes in vast quantities and even with explosive violence when no molten rock is visible. The resemblance of an eruption of a mild character, as when a volcano is in the Strombolian stage, to the boiling of mush in a tall vessel through the action of heat applied at the bottom, illustrates the action that is witnessed in many volcanoes. In this explanation and in most others that have been suggested, steam is appealed to as the main and essential force which causes the molten lava to rise in a volcanic conduit. That steam given off by volcanoes is not the cause of the rise of lava in fissures, however, is indicated by the fact that rocks forming dikes are not vesicular, but, as every geologist knows, are among the most compact and solid of igneous rocks.

It has been shown by Van Hise, apparently on sound principles and correct reasoning, that what may be termed appreciable cavities cannot exist in the earth's crust at a depth in excess of about 30,000 feet. This and other considerations lead to the conclusion that the portion of the earth that is water-charged is the outer layer of the crust. Beneath the sea and land alike, except perhaps in desert regions, the rocks are filled with water, probably to the depth of several thousand feet. In deep mines and wells, with few exceptions, the rocks are moist and usually abundantly water-charged.

Molten magmas, rising through fissures and approaching the earth's surface, would invade a water-charged

zone. The molten rock, on coming in contact with water in the rocks, would vaporize it, or even cause a dissociation of its elements. It is known that many substances, especially when heated and under pressure, have the power of absorbing gases. Molten rock would, it is believed, absorb the steam and gases generated by coming in contact with water, and allow them to escape when pressure is relieved or the temperature lowered. A magma forced through the superficial water-charged layer of the earth's crust, and reaching the surface, would, on account principally of relief of pressure, give off its occluded steam and gases. If the lava was highly liquid, this would take place by a boiling process, the steam and gases escaping quietly; but if the lava was viscous, the expansion of the steam would be retarded until its pent-up energy was relieved by an explosion. If the molten lava came in contact with a considerable volume of water, a violent explosion would be the inevitable result.

The above considerations seem to indicate that steam given off by volcanoes is derived from the water-charged rocks through which the lava passes in the upper portions of their conduits, and also that it is distinct in origin from the pressure and heat manifested in connection with it.

What is known as dry fusion, that is, the melting of substances from which water is excluded, requires in many, if not in all, instances a much greater degree of heat than when water is present, or what is termed aqueo-igneous fusion. We may reasonably conclude, therefore, that a magma rising in a fissure and entering the water-charged portion of the earth's crust would tend to become more fluid. At the same time its energy derived from pressure on the reservoir from which it came would

be increased by the expansive energy of the steam generated. Lava which would not reach the surface by reason of the pressure on its reservoir, might, for this reason, acquire sufficient energy to bring on a surface discharge. Eruptions when water-charged layers are present might therefore be expected to be more numerous than in arid regions. This question has some bearing on the marked association of volcanoes with the ocean, frequently appealed to as showing that sea-water gaining access to heated rocks is one of the main causes of volcanic eruption, but this matter will be considered later.[1]

The instance observed by Squire, cited on a previous page in connection with the description of a young volcano in Nicaragua, in which an explosive eruption occurred in connection with the first heavy rainfall that followed the loss of energy after an eruption, is of interest in connection with the considerations just offered. The effect of the rain seems to have been analogous to what would happen if water should be poured on a bed of highly heated furnace-slag; that is, a steam explosion occurred.

There is negative evidence also which tends to show that deeply seated magmas are not in the explosive condition that frequently characterizes volcanic eruptions. We learn from physical students that the tension of water vapor increases with increase of temperature at more than a simple ratio. If the earth's interior is vapor-charged, it must be in a state of vastly greater tension

[1] I have attempted to correlate volcanoes with humid climates, but although a large majority of volcanoes do occur in humid regions, yet as the surface rocks are nearly everywhere water-charged, there does not seem sufficient reason for concluding that this is an important condition governing their distribution.

than is known from physical experiments or is manifest by the most stupendous volcanic explosion. The effect of water in large volumes on coming in contact with highly heated rocks is illustrated by the eruption of Krakatoa, when something like one cubic mile of rock was blown to dust. If the excessively heated rocks of the earth's interior are steam-charged, the tension under which they exist must be at least as many times greater than the explosive energy manifest at Krakatoa as the volume of vapor in the earth's interior exceeds the volume of steam that caused the explosion in the Strait of Sunda. I know of no way by which to make a quantitative measure of the tension of the steam in the earth's interior, under this hypothesis, but seemingly the comparison just made is sufficient to show that under the supposition that the steam given off by volcanoes is derived from the earth's interior and that the highly heated inner sphere of the earth is steam-charged, we would indeed be "living on a volcano." With such a vast volume of superheated steam within the earth, the crust would be at once blown to fragments. Besides, under the generally accepted theory that the earth was at one time much hotter than at present and has cooled from a molten condition, steam, if originally absorbed by the molten magma, must have escaped before a crust could form. The consideration of what must follow in case a vent for the imprisoned steam in the earth's interior, under the supposition that the highly heated interior is steam-charged, was once opened, as in the formation of a volcano, is again evidence that such vast tension as the hypothesis implies does not exist within the earth.

Both positive and negative evidence thus tend to show that volcanic magmas rising in fissures and nearing the earth's surface, acquire steam from the water-charged rocks traversed. As the water-charged portions of the earth are superficial, volcanic magmas only acquire explosive energy on reaching the outer portions of the crust. The influence of various volumes of water in the paths of ascending magmas, and the character of the explosions which would accompany their coming together, remain to be considered.[1]

Source of the Heat of Volcanoes.— If the reader agrees with me that the source of the steam given off by volcanoes is in the superficial portions of the earth's crust, it will be easy to understand that the source of volcanic heat and the source of the force that causes molten lava to rise through fissures are distinct and should be separately considered.

From what is now known concerning the progressive increase in temperature with depth below the earth's surface, it follows, as has already been assumed, that the source of the heat manifested in volcanic eruptions is the general internal heat of the earth. That is, it is mainly and essentially under the best hypotheses we have concerning the origin of the earth, the residual heat of a once molten globe.

Source of the Pressure which causes Molten Lava to rise in Fissures.— The pressure to which the rocks composing the earth are subjected increases with depth. Even in the lower portion of what is designated as the earth's

[1] A concise discussion of the causes of volcanic action, accompanied by many references to original treatises, may be found, Prestwich's "Geology," Vol. 1, 1886, pp. 210–216.

crust, the pressure is so enormous that we might easily be led to the conclusion that open fissures could not be formed. The fact, however, that dikes occur in many regions and frequently in large numbers, shows that the crust has been broken in thousands of localities, and the fissures formed filled by molten rock injected from below. That the fissures thus filled were formed below thousands of feet and even tens of thousands of feet of rock is proven by their occurrence in regions that have suffered that amount of erosion.

In spite of the natural conclusion that fissures could not be formed in rocks under a vast weight of superimposed strata, we have the well-known fact that they have been formed in practically countless numbers in such situations. An explanation of this apparent anomaly is furnished by the hypothesis that the deeply seated rocks, on account of their high temperature, are in what has been termed above a potentially plastic condition. As soon as a break is formed, pressure is relieved; the rocks to which the break penetrates at once become plastic and probably in many instances highly fluid, and on account of pressure on all sides, except that in which movement is rendered possible by the presence of the fracture, are forced into the opening and rise toward the surface.

Although deeply seated rocks are under such enormous pressure that fracture seems impossible, yet the potentially plastic rocks to which the deeper fractures penetrate are under a pressure of an equal order of magnitude. As pressure increases with depth, the pressure on the deeply seated and potentially plastic rocks are subjected to greater lateral pressure than that which tends to close the

breaks formed in the rocks above them. If these premises are correct,—and there seems to be no way of escaping the conclusions reached,—the result would be that the highly heated rocks reached by a fissure would at once become plastic and would be forced into the break, and would tend to press its walls wider apart. The extent to which a magma would rise in a fissure would depend on several considerations; chief among which would be the pressure on the reservoir from which it came, and the resistance it encountered as it rose. The pressure would be determined by the depth of the reservoir. The resistance met with as the magma was forced upward would be regulated by the size of the break, its regularity, temperature of the magna, lateral pressure tending to close the break, etc. All of the retarding influences, except perhaps the last, may be designated by the term *friction*. There would be friction against the sides of the fissure, and internal friction in the magma itself, each of which would depend largely on temperature. As the temperature decreased by conduction, etc., the magma would become less and less plastic, the friction of flow would increase, and, finally, when solidification ensued, the motion would cease. For these reasons, a magma entering a large fissure would tend to rise higher than in a narrow fissure. Dikes deep within the earth's crust should, therefore, be more numerous than in its surface portion.

The study of fractures and faults in the earth's crust has shown that such breaks are seldom due to continuous smooth-sided fractures, but are rather splintering breaks, which overlap and cross one another, with many offshoots. They are more often belts of intersecting fractures

than single clean-cut gashes. A magma rising in such a belt of fracture would have to force its way from one break to another, and would send off many branches. I think that all geologists will admit that these considerations agree with what is found when dikes are studied.

From what has just been stated, it follows that the resistance to be overcome as a magma rises toward the surface becomes greater and greater; as will be shown later, compensation for this progressive increase in resistance is found when the water-charged portion of the earth's crust is reached and steam is generated.

The considerations just offered, I trust, will make it clear that the source of the heat manifested in volcanoes, and the source of the pressure which causes a magma to rise in a fissure, are distinct; and that the force tending to inject a magma into a fissure is the pressure of the earth's crust on the potentially plastic reservoir from which it flows.

Differences in Volcanic Lavas.—Objections have been made to the hypothesis that volcanoes derive their lava from the highly heated interior of the earth, on the ground that different volcanoes erupt lava of different composition, and that changes occur in the composition of the lava extruded at different times from the same vent.

These objections were valid so long as the interior of the earth was thought to be in a molten condition. If, however, we consider that the earth beneath the cold, outer shell is solid by reason of pressure, but becomes plastic as soon as pressure is relieved, the difficulty disappears. The highly heated interior is evidently not homogeneous, as is shown by the products of volcanoes, and as is known also from pendulum observations.

Under the hypothesis here advanced, a local relief of pressure, due to the opening of a fissure in the cooled crust, would be followed at once by a local change of the highly heated rocks penetrated, to a plastic or fluid condition. The nature of the magma rising in such a break would depend on the composition of the heated rocks reached, and from what we know of the composition of both plutonic and volcanic rocks, evidently differs with both lateral and vertical distribution.

The reason for variations in the composition of the earth's interior is beyond our present knowledge, unless perhaps, as may be suggested under the meteoric hypothesis, the earth has been formed by the coming together of meteoric bodies of various composition. It is known that portions of the earth's crust have been weighted by sedimentation and depressed, so that matter formerly at the surface has passed to the highly heated interior. Such transfers of portions of the crust to the interior would produce heterogeneity in the subcrustal portion, and in the very region, as will be shown later, where volcanoes most frequently occur, that is, on the borders of continental areas.

Independence of Neighboring Volcanoes. — Another objection urged with consistency against the supposition that the earth's interior is in a liquid condition, is that neighboring volcanoes frequently erupt independently and without sympathy one with another. A lofty volcano is sometimes in activity, while a much lower but still active neighboring crater is quiescent. Under the hypothesis here advanced, this objection disappears. If the earth's interior is solid, but in a potentially plastic condition, and branching and irregular fractures are opened from time to time in the

crust through which magmas are forced out, it is evident that neighboring fractures may be independent of each other, and also that branches of a main fracture may become closed and opened independently.

Origin of Fractures in the Earth's Crust. — In reference to the general cause which produces fractures in the earth's crust, an appeal is commonly made to the effect of the shrinking of the earth on cooling, and the folding and breaking of the rigid crust in order to conform with the shrinking interior. Beyond this general explanation it is not practicable to go in this elementary treatise.

Under the hypothesis of a cooling globe it may be surmised that while the crust was thin, folding would go on more easily than when a greater thickness was reached; and that as greater rigidity was attained, fractures would become more common. As the crust thickened, also, its weight would become greater, and hence the pressure on the still highly heated interior augmented. The conditions leading to the formation of volcanoes should, therefore, increase, at least for a time, as the earth cooled, but as the crust became thicker and more and more rigid, the conditions favoring the extrusion of lava at the surface would be expected to decrease and finally cease. With a thin crust and comparatively small pressure on the highly heated interior, an adjustment of the crust to the shrinking interior would be secured by a moderate extrusion of lava from many breaks; but as the crust increased in thickness, greater eruptions from a decreased number of fractures might be expected.

The geological history of the earth seems to be in harmony with these general considerations, since, in North America at least, there is comparatively little evidence of

volcanic action previous to the Jura-Trias. The great volcanoes, not only of this continent but of the world, belong to Tertiary and more modern times. This is not because erosion has removed the more ancient volcanoes, as is shown by the fact that "basal wrecks" of volcanoes of older date than the Mesozoic are rare. This is perhaps unsound reasoning, since many "basal wrecks" must be buried beneath later sediments. Geological evidence seems to show, however, that volcanic activity increased with geological ages, and reached its maximum in Tertiary times. This same line of reasoning leads us to expect fewer volcanoes in the future, owing to the constantly increasing resistance to the passage of magmas from the interior to the surface through the thickening crust, but fissures once opened should give origin to volcanic phenomena on a grand scale. A decrease in the number of volcanoes should be accompanied for a time by an increase in size, but when the crust attained a great thickness all surface manifestations of the internal heat should cease even before the condition of a completely cooled globe is reached.

Association of Volcanoes with the Sea. — As has frequently been pointed out, volcanoes, with but few exceptions, are situated on the sea floor or on islands and along the borders of continents. This has been assumed as evidence that the presence of sea-water, or perhaps more properly of a body of surface water whether connected with the sea or not, is one of the conditions controlling the origin of volcanoes; the hypothesis, still current to some extent, being that sea-water gains access to the highly heated rocks of the earth's interior either through fractures or by percolation, and leads to the generation of

steam, which is followed by eruptions at the surface. The idea of a deeply seated origin for volcanic rocks, and the independence of the sources of the heat and pressure, do not enter into this hypothesis.

In support of the hypothesis that volcanoes are initiated by the access of sea-water to the highly heated rocks beneath the crust, it has been pointed out by various geologists, that the gases evolved from volcanoes are frequently such as might be produced by the decomposition of sea-water. It has been shown, notably in the case of Vesuvius, that the country about a volcano after an eruption is sometimes whitened over large areas with common salt. The force of this argument, however, is weakened when we remember that volcanic conduits frequently pass through great thicknesses of stratified rocks, which are sea sediments and were changed at the time of their deposition with saline water. Many portions of the outer layers of the earth are known to be saturated with sea-water; and in several regions, some of them of broad extent, there are beds of rock salt. Evidently, then, volcanoes might erupt substances like those contained in sea-water, or gases formed by their decomposition, without any direct connection with the sea.

The origin of the steam of volcanoes, as has been shown, can be accounted for by the passage of molten lava through water-charged rocks. It has been pointed out that the rocks beneath land areas are generally water-charged from surface precipitation. These considerations, it seems to me, remove all support from the hypothesis that volcanoes have a necessary connection with surface water-bodies. The fact still remains, however, that volcanoes occur principally on the borders of continents.

Several geologists have studied the distribution of oceans and continents and sought to explain their origin. It is known that these greater features of the earth's surface have been somewhat well defined for geological ages. In fact, the continents and oceans were outlived before the appearance of the first known fauna on the earth. Dana has sought to explain the origin of continents by saying that their borders were "original lines of weakness" in the earth's crust, and that movements along these lines, or more properly, belts, have been continued to the present day. What determined the original lines of weakness remains unexplained. The questions that here present themselves are too wide-reaching to be discussed at this time, even if I had the ability to do them justice; but enough seems clear to explain the distribution of volcanoes, and to show that they have no direct and causal relation to existing water-bodies. The borders of continents, as is well known and, I think, universally conceded by geologists, are belts along which repeated movements have taken place. They are belts along which the folding and fracturing of the earth's crust have been most frequent. Being belts in which fractures have occurred, they are the regions where molten rock forced through the fractures has given origin to volcanoes. The presence of volcanoes on the borders of continents is, then, the result of some antecedent condition, which established belts of weakness in the earth's crust. Along these belts, movements have taken place on account of the earth's shrinking on cooling, and also by reason of the shifting of material on the earth's surface, and possibly other causes.

There are lines of fracture remote from the sea, — as in the Great Basin region, to the east of the Sierra Nevada, — and in such regions volcanoes occur hundreds of miles inland. The only logical conclusion in reference to the distribution of volcanoes, which seems at all tenable, is that they occur where fractures have been made in the earth's crust, and that they are not necessarily dependent on the distribution of land and water on the earth's surface. The association of volcanoes with the borders of continents must, therefore, be considered as of the nature of a coincidence, the boundaries of continents and the distribution of volcanoes having been determined by a common cause.

Influence of Water on Volcanic Eruptions. — Although there does not seem to be a genetic relationship between volcanoes and surface waters, yet water does play an important part in determining the nature of volcanic eruptions and even in producing discharges of molten rock.

If we imagine a fissure formed in dry rocks, and a molten magma forced through it to the surface, the result would be an overflow of lava. If the lava is in a condition of "dry fusion," — that is, fusion without water above that chemically combined, — the outflow at the surface would be similar to what occurs when molten slag is drawn off from a furnace. The eruptions would be of the quiet type, and not accompanied by explosions. Under these conditions, the lava must lose more and more heat the higher it rises in the earth's crust, and consequently becomes less and less plastic. In many instances, it may be imagined the lava would rise near to the surface, but be checked in its ascent by

becoming too rigid to be forced out. The friction of flow would increase in an inverse ratio to the plasticity of the magma. If, however, this stage is reached in water-charged rocks, steam will be generated and absorbed, the highly heated lava will become more fusible on account of the pressure of occluded steam, and therefore capable of being forced out by a pressure that it would successfully resist if it had not come in contact with water. Viscous lava, also, on coming in contact with large bodies of water in the earth's crust, might generate sufficient steam to blow out a passageway to the surface.

Even from this brief statement, it will be seen that water in the superficial portion of the earth's crust has an important influence not only in varying the character of volcanic eruptions, but of inducing surface discharges in cases where the pressure from beneath fails to force a magma to the surface. Force is added to the upper portion of a lava column which is not present before it enters the water-charged rocks. This force — the tension of steam — is added to the force derived from pressure deep below the surface, and is accountable for many of the phenomena attending eruptions. The importance of this added force is so great that it has been mistaken for the primal cause of volcanic extrusions.

In brief: during volcanic eruptions, there is a rise of molten or plastic rock through fissures, and a descent of surface water through fissures and by percolation; the meeting-place of these two important elements is in the superficial portion of the earth's crust. The maximum depth to which surface water penetrates is probably not over 30,000 feet, and, in general, the quantity of water

present in a given volume of rock increases from near that depth to the surface. In addition to water percolating downward, there is water in the case of sedimentary layers which was retained by them at the time of their deposition.

OTHER HYPOTHESES

The explanations offered in the preceding portions of this chapter, in reference to the nature and origin of volcanic eruption, differ from most of the previously entertained hypotheses that have been advanced to account for volcanic phenomena; and, in justice to the student who obtains his first introduction to volcanoes from these pages, it is proper that at least some account of explanations previously offered should be given. Space will not permit more than a glance into this branch of the subject, but, from the references given, the reader will be enabled to compare hypotheses for himself and be led to independent conclusions.[1]

Chemical Hypothesis. — In an early stage in the study of volcanoes it was suggested that the interior of the earth consists of unoxidized alkaline metals, and that the penetration of water caused oxidation to take place with the production of great heat. This hypothesis, although advocated by Davy and Daubeny, was finally abandoned by the former, and now is of historic interest simply. The products of volcanoes show that conditions even

[1] Discussions of various hypotheses advanced to account for volcanic phenomena may be found in the following books: G. P. Scrope, "Considerations of Volcanoes," London, 1825. J. W. Judd, "Volcanoes," New York, 1881, pp. 331–369. Joseph Prestwich, "Geology," Vol. I, 1886, pp. 210–216. Joseph Prestwich, "On the Agency of Water in Volcanic Eruptions," in Royal Society of London, Proceedings, Vol. 41, 1886, pp. 117–173.

remotely similar to those postulated do not exist in the regions from which volcanic rocks are derived.

Mechanical Hypothesis. — It has been suggested by Mallet[1] that when movements in the earth's crust occur, as when rocks are folded or faulted, the friction is such that sufficient heat is produced to fuse rocks and bring on volcanic conditions.

The movements of rocks referred to unquestionably result in the conversion of some of the energy expended into heat. Such earth movements, however, are believed in most instances to progress slowly, so that the heat produced is diffused by conduction, etc., and a temperature necessary to fuse rocks would not be expected to be reached in most instances. Besides, in many regions, as for example in the Appalachians, there has been intense folding and much faulting, but volcanoes are absent. The walls of great faults and the surfaces brought in contact by overthrusts do not, so far as observed, exhibit evidence of fusion having occurred. Recent theories concerning the metamorphism of rocks ascribe profound changes in mineralogical and chemical composition to the effects of dynamical changes, which certainly favors the views expressed by Mallet. On the whole, however, the mechanical hypothesis has not been generally accepted by geologists, and does not seem to adequately explain many of the phenomena associated especially with intruded rocks, which, so far as their genesis is concerned, must be studied in connection with surface extrusions.

Steam Hypotheses. — The consideration that steam is the main propelling force which causes lavas to rise

[1] "On Volcanic Energy," Philosophical Transactions of the Royal Society, 1873, p. 147.

through fissures in the earth's crust, has already been referred to, and several objections to it suggested. Hypotheses based on the idea that steam, which plays such an important part in many eruptions, is in reality the main cause of the rise of lava from deep within the earth, have been advanced with various modifications by Scrope,[1] Lyell,[2] Judd,[3] Reade,[4] and others.

Objections to the hypothesis that steam is the main source of the energy which brings about volcanic eruptions, have been formulated by Prestwich, and still remain unanswered. In addition to the considerations referred to, others might be enumerated in reference to the nature and origin of intruded igneous rocks, for the reason, as already urged, that intruded and extruded rocks result from variations in a single process. The criticisms on what I have termed the "steam hypotheses" by Prestwich[5] are as follows:

"(1) If the molten mass were so permeated by gases and vapors, the eruption of lava and the discharge of vapors would always be concurrent, and there could be no discharge of the one without the accompaniment of the other; whereas there are many eruptions which are altogether explosive, while in other eruptions — many of them very large — the flow of lava is effected quietly and without the detonations and ejections caused by the explosion of vapors. (2) Another objection is that all lavas would be more uniformly scoriaceous, and that vapor

[1] "Considerations on Volcanoes," London, 1825, pp. 17, 66.

[2] "Principles of Geology," tenth edition, Vol. II, p. 221.

[3] "Volcanoes: what they are and what they teach," New York, 1881, pp. 33, 39, 331–369.

[4] "The Origin of Mountain Ranges," London, 1886, pp. 253–265.

[5] Joseph Prestwich, "Geology," Vol. I, 1886, pp. 212, 213.

bubbles would show themselves more generally; but there are lavas which are perfectly compact, although they have outflowed under the usual atmospheric pressure. (3) Again, it is difficult to conceive how these vapors and gases could have become incorporated with the molten magma, unless we admit, with Dr. Sterry Hunt, that between the solid crust and the solid nucleus of the earth, there is a layer consisting of the outer part of the originally congealed mass, disintegrated and modified by chemical and primitive mechanical agencies and impregnated with water, now in a state of igneo-aqueous fusion; or with Mr. Osmond Fisher, who connects volcanic eruptions with the extravasation of a primogenial water-substance in the molten magma. Otherwise, that water could find its way down to the volcanic foci *through* the crust of the earth is highly improbable, as a point must be reached where there is reason to suppose the tension of the vapor will equal the hydrostatic pressure of the descending water and stay its course. Further, if such were not the case, not only the volcanic, but likewise the plutonic, rocks would have been subjected to ejection under the same conditions and with similar subaërial results.

"Another hypothesis, which also assumes water to be the prime motor of eruption, but considers its introduction to the volcanic foci to be coincident with the eruption itself, supposes fissures to be formed in the bed of the sea, by which a direct passage is opened for the sea-water. The objections to this hypothesis are, that it is not possible to suppose a fissure down which water could have passed without its forming a passage for the escape of the lava itself; nor can we conceive the steam, if so

produced, could have had the force to eject a column of lava of the height required to reach from the volcanic foci to the summit of the volcano, or that it would take the longer, more resisting, and more indirect channel in presence of the open and unobstructed fissure."

An exhaustive discussion of all the various hypotheses that have been advanced to account for volcanic phenomena, is impracticable at this time, but this chapter would be markedly incomplete without a reference to a modification of the steam hypothesis recently proposed by Shaler.[1] The essential features of the hypothesis referred to are that oceanic sediments of which most stratified rocks are composed, are charged at the time of their deposition with sea-water, and may attain great thickness. As layer on layer of strata are laid down, the basement portion of the pile becomes heated by conduction from the earth's interior; the successive layers acting like blankets in retarding the escape of the heat of the earth. As stated by Shaler: "We thus see that in the water imprisoned in the deposits of the early geological ages and brought to a high temperature by the blanketing action of the more recently deposited beds, we have a sufficient cause for the great generation of steam at high temperatures, and this is the sole *essential* phenomenon of volcanic eruptions. We see also by this hypothesis why volcanoes do not occur at points remote from the sea, and why they cease to be active soon after the sea leaves their neighborhood. . . .

"The foregoing considerations make it tolerably clear that volcanoes are fed from deposits of water contained

[1] N. S. Shaler "Aspects of the Earth," New York, 1889, pp. 46–97. Also, "Scribner's Magazine," February, 1888.

in ancient rocks which have become greatly heated through the blanketing effects of the strata which have been laid down upon them. The gas which is the only invariable element of volcanic eruptions is steam; moreover, it is the steam of sea-water, as is proven by analysis of the ejections. It breaks its way to the surface only on those parts of the earth which are near to where the deposition of strata is lifting the temperature of water contained in rocks by preventing, in fact, the escape of the earth's heat."

In answering probable objections to this hypothesis, its author states that the only serious question arises in reference to the thickness of the rocks which have been laid down on the sea floor. In this connection it is remarked: "Hardly any geologist will doubt that it is entirely within bounds to assume that thickness to exceed twenty miles. It may well have attained twice or thrice that depth since the geological ages began."

In reference to the statements made in the last quotation, it must be acknowledged that the thicknesses of stratified rocks assumed are purely a matter of opinion; no such thickness of stratified beds in one pile has ever been observed. Instead of subscribing to the statement that geologists are practically agreed as to the vast thickness of stratified beds, I, for one, must dissent from such a conclusion until proof is advanced to sustain it. Whatever the aggregate thickness of sedimentary beds deposited during various geological ages may be, the essential part of the hypothesis is that the sedimentary beds should be immensely thick in a given locality.

Marine sedimentation usually continues only so long as subsidence carries the added material below sea level.

An increase in the thickness of sedimentary beds will cause a rise of temperature in their basal portions especially, as claimed by Shaler, but this means an increase in volume, and, as pointed out by Reade and others, an elevation of the surface. It appears, therefore, in localities where thick sediments accumulate, that an excessive thickening should be checked, if for no other reason, by elevation due to rock expansion, which would carry the surface above sea level, and such excessive thicknesses of stratified beds, as is essential to the hypothesis referred to, could not be expected to occur.

One of the deepest sections of stratified rocks, consisting largely of Paleozoic sediments, yet measured in America, occurs in the middle Appalachian region, but volcanoes and volcanic rocks of post-Paleozoic date are absent. The thickness found is not enough, to be sure, to meet the requirements of this hypothesis, but it appears to be one of the best test cases that can be suggested.

The claim made in the hypothesis under consideration — that steam is the sole essential phenomenon of volcanic eruptions — has been considered on previous pages, where the evidence of the independent origin of the pressure, heat, and steam manifest in volcanoes has been presented. If the reasons for considering the essential independence of these chief causes for volcanic phenomena are valid, it is evident that to account for the escape of steam during a volcanic eruption will not furnish a complete theory of the origin of volcanoes.

The student will find on reading Shaler's very interesting and suggestive paper, that the essential connection between volcanoes and subterranean intrusions of molten rock is not fully recognized. When the fact that dikes,

intruded sheets, plutonic plugs, laccolites, subtuberant mountains, and volcanoes result from variations in one general process, is admitted, and it seems to me the conclusion is well founded, this general view at once does away with the assumption that steam is the sole cause of volcanic phenomenon. These same considerations must lead us to put aside the long-cherished hypothesis that there is an essential and, to volcanoes, a vital connection between extrusions of molten rock and the distribution of surface water-bodies.

In all of the hypotheses that have been advanced in which steam is considered as the prime motor, the point of view is that obtained by an observer looking down into craters like those of Vesuvius or Stromboli, when in mild activity. The phenomena of the boiling of the liquid lava and the escape of great bubbles of steam are then the prominent facts. To account for the steam observed in such cases, seems to be the chief feature of the problem; the rise of the molten lava from miles below the surface, the conditions under which it exists in the reservoir from which it flows, and the changes it undergoes as it nears the place of discharge, are lost sight of in the presence of the striking activity in progress at the summit of the lava column.

If in imagination we change the point of view, and see the reservoir miles below the surface, the conduit, perhaps with many branches leading upward, the upward flow of the molten rock through the conduit, the descent of surface water, — and also the presence of water in stratified beds, — to meet the rising magma, etc., it must appear that the "sole essential phenomena" to be accounted for are not the presence of steam.

CHAPTER VIII

THE LIFE HISTORY OF A VOLCANIC MOUNTAIN

One of the phases of modern geographical study is the tracing of the successive changes that the various features of the land pass through from their initiation to their disappearance. As is well known, even the most magnificent mountains that give diversity to the earth's surface at the present day, have had their time of birth and growth, and have perhaps reached full maturity, but are one and all crumbling before the attacks of the destructive agencies of the atmosphere and will ultimately be removed. The record of such a series of changes in topographic forms from youth to maturity, old age and final disappearance, may with propriety be termed a life history.

The life history of a volcanic mountain should evidently begin with the changes deep within the earth that lead to its birth. These prenatal causes, however, are such an intimate part of a still greater history — the development of the earth itself — that it would lead too far from our immediate theme to begin a review of the history of a volcanic mountain with a discussion of the conditions which antecede its appearance as a topographic feature.

When a fissure is formed in the earth's crust through which molten rock is forced upward to the surface, there may be an overflow throughout a considerable extent of the break and a fissure eruption ensue; but more commonly

the escape of lava is restricted to certain circumscribed localities about which volcanic mountains are built up. Whether a volcano shall belong to the quiet or the explosive type depends on various conditions, some of which have been discussed in the preceding chapters. Volcanic eruptions thus present great diversity and lead to topographic changes with widely varying characteristics. A complete discussion of the life histories of the many topographic types due to igneous extensions would embrace the origin, dissection, and disappearance of vast lava plains like those drained by the Columbia; the birth, growth, decline, and death of mighty domes with plateau-like summits of the Hawaiian type, and of the conical piles of lapilli and scoria represented by the sacred mountain of Japan. It is difficult to group such varied phenomena in a single picture. Let us, instead, select a single individual from the most numerous class of volcanic mountains,—the composite cones formed largely of projectiles, but bound together by lava streams and dikes,—and endeavor to review the principal changes it experiences during its life span.

It is possible that the aborigines of the Pacific coast witnessed the advent of some of the giant volcanic peaks which now give dignity and grandeur to the scenery of that promising land. Could we have stood with some primitive hunter, armed with flint-pointed arrows and stone axe, on the granite hills commanding a view of the fair Tertiary plains of Oregon and Washington, we would have beheld a sylvan scene as beautiful in its varied charms as any landscape our broad continent presents to-day. Let us take such a backward journey. To the flight of fancy a million years are but as a day.

From our commanding station on the Tertiary uplands, forest-covered hills and broad verdant valleys are spread before us. A gleam as of burnished silver here and there amid the dense forest of the plain marks the course of a noble river. Lakes enclosed by walls of verdure add an indescribable charm to the scene. Between the banks of purple formed by the distant hills, we catch glimpses of the shimmering sea. The general features of the broad landscape, the shadows of passing clouds on the summer foliage, and the ever-varying tints of sea and sky are the same as the dwellers of the earth see to-day, — and yet do not see, so familiar are they. But little in the varied details of the scenes about us is familiar, except the crystals in the granite beneath our feet. Should we descend from our chosen station, we would find that the trees and flowers in the forest are strange to us. The birds and insects that fill the air with music are all unfamiliar. The mammals that roam the forest and haunt the river banks and lake shores are still more novel. We have gone so far back in the history of the earth that the plants and animals are the ancestors of the present flora and fauna; yet the Tertiary is only the day-before-yesterday of geology. We are in the sunny summer-tide of the earth which preceded the Glacial winter.

Our reveries are broken by an earthquake shock. A fissure has opened in the broad, forested plain, and a vast column of vapor is rolling heavenward. Explosions hurl great rocks high in the air, some of which fall in the adjacent forest. The vapor column is darkened by dust, which drifts away before the wind, and for miles to leeward the vegetation is whitened as if by snow. The trees are denuded of their branches and in places buried

from sight. A roar as if of mingled thunder crashes makes the air vibrate. With each explosion the earth trembles. The cloud of dust-laden vapor expands and soon the entire land is in shadow. As the air grows dense about us, the sun assumes strange hues. Lightning flashes seem to tear the dense veil asunder, but the accompanying thunder is lost in the deafening roar of escaping steam and the crash of countless explosions. Although it is midday, the blackness of a starless midnight soon conceals the dreadful scene. Strange cries of terror-stricken beasts come from the neighboring forest. Birds of unfamiliar plumage, regardless of our presence, perch on the rocks about us. Our Indian companion prostrates himself in worship.

Days pass before the sun again appears and reveals a scene of death and desolation where before all was life and beauty. Where the vapor was first seen to rise, there is a conical hill of black and still steaming rocks, — an infant volcanic mountain. In its summit we can discern an opening or crater, from which a great volume of steam is rolling out. Occasionally the vapor column is darkened by dust and scoria shot upward by explosions within the crater. During periods of decreased activity we might walk over the desolate plain of lapilli and dust, and if a strong wind should be blowing, climb the wall of the crater and look down upon the red-hot, liquid rock that surges in its depths. At night the light from the molten lava is reflected by the cloud above it. The under surface of the expanded summit of the vapor column is all aglow with lurid light, while the undulating upper surface is dark or perhaps has a silvery whiteness in the moonlight.

At varying intervals for years the activity within the crater becomes more intense. The molten rock rises to the lowest place in the rim of the crater and sends a fiery stream down its side and far out on the plain. Explosive eruptions occur from time to time, and again and again lava wells out, sometimes in such volume as to deluge the surrounding country. Steam rises from the broad lava fields, and at night they glow with a dull reddish light. With each eruption the hill is built higher, and at length attains the dignity of a mountain.

The volcanic mountain is approaching maturity. It rises with all the symmetry and freshness of youth, as a cone with long, smooth, gently concave slopes, which merge imperceptibly with the surrounding plain. Above its sharp summit a cloud is usually visible which the winds distort into many fantastic shapes.

After centuries, marked by mild eruptions, with long intervals of rest, the cloud disappears from the mountain's summit, and the snow lies deep on its sides even in midsummer. The life of the volcano seems to be ended, and the mountain to have reached its full stature. But earthquakes, mild at first and gradually growing more and more severe, indicate that renewed energy has been given to the plutonic agencies deep within the earth. Suddenly, without definite warning, the land in every direction is shaken by severe earthquakes which succeed each other quickly. Then comes a mighty crash. The earth seems shaken to its centre. The land is again shrouded in darkness. When the gloom lessens, we find that the symmetrical mountain has been shattered. Its summit for a third of its height has been blown away, and the rocks of which it was composed disintegrated

and scattered as lapilli and dust over thousands of square miles of land and sea.

The mountain is now a truncated cone with a bowl-shaped depression in its summit, three or four miles in diameter and over 2000 feet deep. Of such shape and size was Vesuvius in the time of Spartacus. Great as has been the catastrophe, the life of the mountain is not ended, but instead has renewed its youth. Activity marked by both explosive eruptions and lava flows ensues. A new cone rises within the vast crater and in time overtops its rim. Renewed eruptions rebuild the mountain. It becomes higher and of grander proportions than before the great explosion that truncated its summit, but remnants of the rim of the great crater can be detected at certain localities on its sides.

Centuries pass without marked changes, but a slow decline of energy is manifest. Lava no longer flows from the crater. The apex of the cone is sharp. The lower slopes are forest-covered.

Earthquakes again agitate the earth. The lofty mountain is rent by fissures, some of which extend from its base to near the summit. Molten lava pours out through these openings and feeds surface flows which devastate the adjacent forest. Some of the molten rock cools in the fissures and forms dikes, which serve to bind together the broken lava sheets, and give greater strength to the structure.

More quiet conditions ensue. Explosions become infrequent and finally cease. The mountain has a height of over 15,000 feet. The vapor cloud that continues to rise from it for centuries after the last eruption may be seen for hundreds of miles when the air is clear. The

vast pile, that has required tens of thousands of years for its upbuilding, has reached its majority. It ranks with the greater of the volcanic mountains of the earth. It is well built. Its form is one of great stability. Apparently it will endure as long as the world lasts. But wait. Soft vapor wreaths gather silently about its sides. Rain falls. During all of the time that the mountain has been growing, there have been destructive agencies at work, but their effects have been more than counteracted by the energy of the plutonic forces striving to build a monument to their memory.

The once molten rock forming the great mountain becomes cold, except deep in the interior. The hard lava, as well as the loose lapilli, crumbles to soil, and forests once more clothe the mountain sides. Near the line marking the upper limit of tree growth, there are broad grass-covered areas with scattered groves of hardy evergreens. The knolls and glades in these natural parks are brilliant with flowers. Above the broad belt of alpine plants, which surrounds the mountain like a garland, are glittering snow fields. A dark line at the summit of the cone indicates that the rocks forming the rim of the crater are still sufficiently warm to melt the snow that falls upon them. Vapor, condensed from passing air currents, forms cloud banners about the summit which drift away in shining folds and resemble the clouds that formerly arose from the steaming rocks. In winter the vast pyramid is of spotless white, relieved by delicate blue shadings where the shadows lie. As time passes, the snows become more abundant, and even in summer much of the mountain is robed in white. The snow hardens into ice. Glaciers

are born, and slowly carve deep channels and broad amphitheatres. The mountain has passed its prime and is gradually yielding to the ceaseless attacks of the destructive agencies of the air.

The summit is no longer sharp, but blunted, and reveals the convex curvature characteristic of weathered rocks. Erosion is most intense, however, midway down the slopes, and it is there the greatest changes appear. The sides of the mountain are no longer graceful, concave curves. The streams of hardened lava become prominent as the softer rocks about them are removed. The dikes are brought into relief in a similar way, and form narrow ridges that may be traced from near the summit down the slopes and far out on the adjacent plain.

For a long time in the past maturity of the mountain, the loose, unconsolidated, fragmental products, of which it is largely composed, withstand the erosive agencies in a remarkable manner. The secret of this is that these loose accumulations allow water to percolate freely through them and thus rob it of the power to erode. The rock fragments near the surface are broken still finer by changes of temperature and by the freezing of absorbed water. But they yield principally and to a great depth to solution. The percolating waters are charged with acids derived mainly from volcanic exhalations, which enhance their solvent power. The rocks are leached of their more soluble minerals and become friable and soft. The fine, clay-like material left by this process as a residue fills the interspaces between the larger fragments, thus checking percolation and admitting of the gathering of the surface waters into rills and brooks. Erosion then becomes more active, and

channels and ravines are carved which increase the diversity of the mountain's sides.

Absorbed in watching the growth of the mountain and the carving of the lines that mark its advancing age, we have, perhaps, been unmindful of the flight of time. The Tertiary age has passed. A climatic change, gradual in its approach, has led to a marked increase in the size and extent of the glaciers flowing from the névé fields about the mountain's summit. The river-like streams of ice creep slowly down the rugged slopes and advance for a score of miles over the adjacent plain. From the extremity of each glacier, a roaring torrent of milky water flows away through a trench-like valley. The mountain is white from base to summit throughout the year. The forests that formerly clothed its sides have been swept away. For tens of centuries the slowly moving ice grinds away the rocks, and great changes in topography are in progress. The névé fields about the higher portions of the peak divide, as they descend, into well-defined glaciers, each of which deepens its channel and intrenches itself in the rocks. The spaces between the radiating canyons excavated by the glaciers stand in bold relief and appear as huge triangles arranged about the base of the mountain. Each of these surfaces spared by the ice erosion presents a sharp angle to the descending current of the névé and divides it as the prow of a vessel anchored in a stream divides the passing current. As the glaciers grind deeper, the upward-pointing angles of the intervening wedges become more and more prominent, and at length appear as secondary peaks, midway up the slopes in which the bordering canyons have been carved.

Within the circle formed by these secondary spires and crags rises the steep-sided central dome.

The geological winter, termed the Glacial period, slowly passes. The glaciers become smaller and shrink within the canyons they have carved. In summer bare rocks appear on the lower slopes of the mountain, but centuries pass before the forest again advances and conceals the desolation and ruin the ice has caused. Flowers again enamel the alpine meadows, but the great dome above is white with perennial snow.

Our mountain has passed its prime and bears the unmistakable furrows of age, but is still majestic. It has reached the stage in its life history illustrated at the present day by Mt. Shasta and its companion in magnificence, Mt. Rainier.

With the slow transformation of the mountain changes have taken place in the surrounding plain. The lava streams which flowed from the volcano during its time of growth, and sought the lowest depressions in the land about its base, have been left in bold relief by the removal of the softer rocks not protected by them, and now appear as prominent tablelands. Beneath the cliffs of columnar basalt forming the boundaries of these mesas the volcanic dust and lapilli is exposed, which was strewn over the land during the earlier eruptions. On searching in these deposits we can find trunks and stumps of trees, relics of the Tertiary forests, now changed to stone. Possibly a bone of some strange mammal, long since extinct, may also reward our search. The teachings of these relics of ancient floras and faunas are in harmony with the ruin of the once mighty mountain, and also bear testimony to the great lapse of time since our volcano was young.

The study of many volcanic mountains in various stages of dilapidation and decay enables one to predict the principal phases that our ideal mountain will pass through in its old age. A century witnesses but little change in its contours and practically none in its height. But tens of centuries will see the outer covering of scoria and lapilli slowly removed. The ice-filled amphitheatres on its sides will be enlarged. The lateral ridges separating them will become sharp, ragged crests, and then crumble to feed the moraines at their sides. The backward cutting of the amphitheatre and canyon will give steep sides to the central dome, and at length the convex summit due to weathering will be broken and spires and crests at a lower level take its place. As the mountain decreases in height, the glaciers that have done so much toward sculpturing its sides will shrink and disappear. The central core of hard lava will be left in relief as the softer rocks about it are removed, and become a prominent topographic feature. For ages this central plug of resistant rock will stand as a mighty tower bidding defiance to storms and frosts, and resemble the volcanic necks now forming such a marked feature of the arid region about Mt. Taylor, New Mexico. Our mountain will then have reached extreme old age. In fact, as a mountain, its life will already have ended. The tower-like mass formed by the central plug will slowly crumble, and at length a rounded hill with weathered boulders at the top will be all that is left. The destructive agencies of the atmosphere are unsparing, however, and even this humble monument to the memory of the once glorious monarch must be removed.

Should the platform on which the mountain was built

be sufficiently elevated above the sea, or if earth movements during the long history we have briefly reviewed have upraised it, erosion will cut away the rocks to an horizon below that of the valley in which the volcano had its birth, and reduce the entire region to the level of the sea. In other words, the land, with whatever topographic forms it may have possessed, will be eroded to base level. A geographical cycle will then have come to an end. Some thoughtful man in the far distant future will walk over the plain beautiful with a new flora, and find the dikes of plutonic rock that occupy the fissures in the earth's crust from which came the material used in building the vanished mountain.

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